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FINAL SUMMARY TECHNICAL REPORT ON TRANSIENT PRESSURE MEASURING METHODS RESEARCH

AMS Report No. 595t

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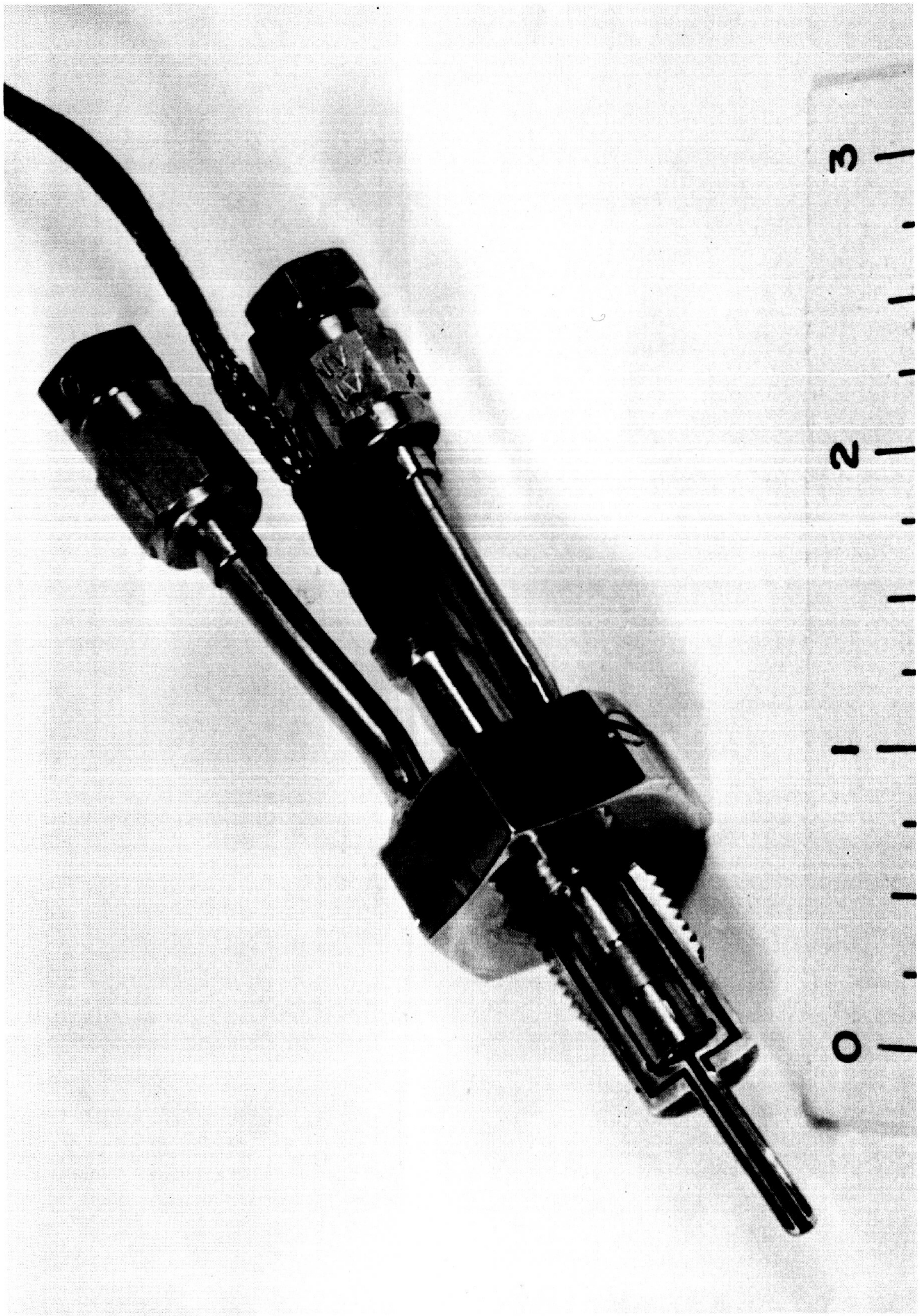

Sectioned Prototype Guggenheim Laboratories Model GL029
Cooled, Small Passage, Gas Bleed, Probe Adapter

FRONTISPIECE

ABSTRACT

This report presents in final summary form five years of research on transient pressure measuring methods applied to liquid propellant rocket thrust chambers. The work was carried out in the Guggenheim Laboratories of the Department of Aerospace and Mechanical Sciences, School of Engineering and Applied Science, Princeton University.

Laboratory evaluations of current transient pressure transducers are presented. Dynamic performance of both uncooled and cooled flush diaphragm transducers of a number of manufacturers is given. Passage connected transducers are evaluated including the Princeton small passage gas bleed technique.

Target characteristics for advanced miniature, cooled, flush diaphragm and passage connected pressure transducers are offered.

The evaluation methods employed in the laboratory and on the rocket test stand are described. The use of a shock tube for evaluating dynamic performance by computer analysis of oscilloscope photographs is discussed fully. The use of the Princeton Sinusoidal Pressure Generator developed under this research for transducer system frequency response measurements is presented. This simple device is especially applicable to passage connected and bleed type transducers. The results of pulse tests and subsequent combustion instability on transducer performance are shown.

Transduction system and operational considerations are discussed in some detail.

Conclusions and recommendations resulting from the work are presented.

Appendixes include a list of twenty publications resulting from this research, a copy of the laboratory evaluation procedure, and details of design, operation and data analysis for the shock tube and Princeton Sinusoidal Pressure Generator.

ACKNOWLEDGMENT

This research was carried out by a number of workers in the Guggenheim Laboratories at Princeton. It was originally led by Mr. Howland B. Jones and subsequently by Mr. J. Preston Layton. Mr. Robert C. Knauer and Mr. John P. Thomas served as Research Engineers. A number of staff and student contributors are acknowledged by authorship of the several publications listed in Appendix B.

Evaluation tests of the transducers in rocket motors were conducted in conjunction with the research in liquid propellant rocket combustion instability under Professor Luigi Crocco and Mr. David T. Harrje at Princeton.

This research was sponsored by the National Aeronautics and Space Administration Office of Advanced Research and Technology under Contract Number NASr-36 since March 1961 with Mr. Henry Burlage, Jr., Chief of Liquid Propulsion Technical Programs, the program monitor. Mr. Jack Suddreth served in this capacity more recently. Technical monitors were Mr. Gerald Morrell and Dr. Richard J. Priem of NASA Lewis Research Center.

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FINAL SUMMARY TECHNICAL REPORT ON TRANSIENT PRESSURE MEASURING METHODS RESEARCH

I. INTRODUCTION

Transient pressure measurements in liquid propellant rocket thrust chambers have been increasingly recognized in recent years as vital to progress in research and development of high performance rocket systems. These measurements are of primary importance duing startup and shutdown and during periods of unstable combustion when operating conditions are especially severe.

The research described in this report was carried out over a period of five years with the aim of understanding the applicable transduction methods and techniques, improving the transducers and their systems and facilitating experimental results.

A. History

It has been evident to many workers in the rocket field for over ten years that accurate transient pressure measurements provide the basic information that is fundamental to understanding and dealing with research and development problems in their field. The very high rates of change and dynamic responses that occur in liquid propellant rocket systems, especially the thrust chamber, characterize the problem. Although pressure is the easiest state property to measure accurately on a transient basis, rocket systems are notorious for extreme operating conditions including low and high temperatures and severe vibrations coupled with a wide range in the enviornment. A satisfactory capability for making these essential measurements has never existed for these reasons and does not exist today.

Continued attempts to deal adequately with the problem in the past have been unsuccessful for a number of reasons. The developing need for the specialized transducers was not recognized broadly. The users never gave proper attention to the overall requirements for these measurements beyond an immediate requirement. In fact, a reluctance to make such measurements was usually shown except on special studies and the transducer characteristics were often not understood. On the other hand, the instrument manufacturers were generally unable or unwilling to assume responsibility for the performance of the transducers as the requirements developed. The manufacturers, usually small concerns with limited resources, were unwilling to invest in instruments of limited sales potential and were able to deliver instruments without guaranteeing their performance. The required performance was, in fact, usually not well understood. Government and other contracting agencies failed to write requirements into the research and development contracts or to support the development of transducers and their auxiliaries. Practically no effort was made to anticipate the need for a specific measurement system performance and support efforts to meet that need with fully developed instruments of known and satisfactory performance. In addition, the fundamental aspects of dynamic measurements were little understood in the field and little attention was given to the education and training of all personnel concerned.

B. Current Status

In the past several years the efforts of individuals in various activities have helped in moving from the situation described above so that all personnel required to solve the continuing and increasingly difficult problems of transient pressure measurements in present and future high performance rocket systems are now alerted and, generally, anxious to participate.

Two transduction methods have found recent applicability to transient pressure measurements in addition to the two primary methods of the past which were the bonded wire resistive strain gauge bridge and variable capacitance methods. The two methods recently applied to transient pressure measurements in rocket motors are the piezo-electric (quartz) crystal and the piezo-resistive semi-conductor (silicon) strain gauge bridge. Transducers based on all four of the above transduction methods are currently available although none are fully developed as described in Section II below.

Evaluation methods for measuring the dynamic and other performance characteristis of transient pressure transducers have been developed and are being increasingly used in many laboratories. Some of these are described in Section III below.

Transducer system and operational considerations have received attention and the indoctrination of professional and other technical personnel is being undertaken.

A somewhat detailed statement of the research results from the work at Princeton that will serve as a background for this report and that described the overall status as of 31 December 1964 can be found in a paper (1)* published in ISA Transactions. It has been supplemented by the most recent Summary Technical Report (2). The subsequent reports and this report will serve as the final statement of our work.

C. Future Prospects

It is hoped that sufficient groundwork has been laid so that further efforts will bring about necessary changes in developed technology and

*Numbers in parenthses refer to publications listed in Appendix A.

outlook to meet the problem of transient pressure measurements in high performance rocket systems of the future. The present status is far from satisfactory and the problem is seen as a continuing one since system performance in the future will be pushed to higher levels of pressure, temperature, and reliability. Some future aspects are presented in the sections below, especially Sections II-B, VI and VII.

II. TRANSDUCERS FOR TRANSIENT PRESSURE MEASUREMENTS IN LIQUID PROPELLANT ROCKET THRUST CHAMBERS

A. Evaluation of Current Transducers

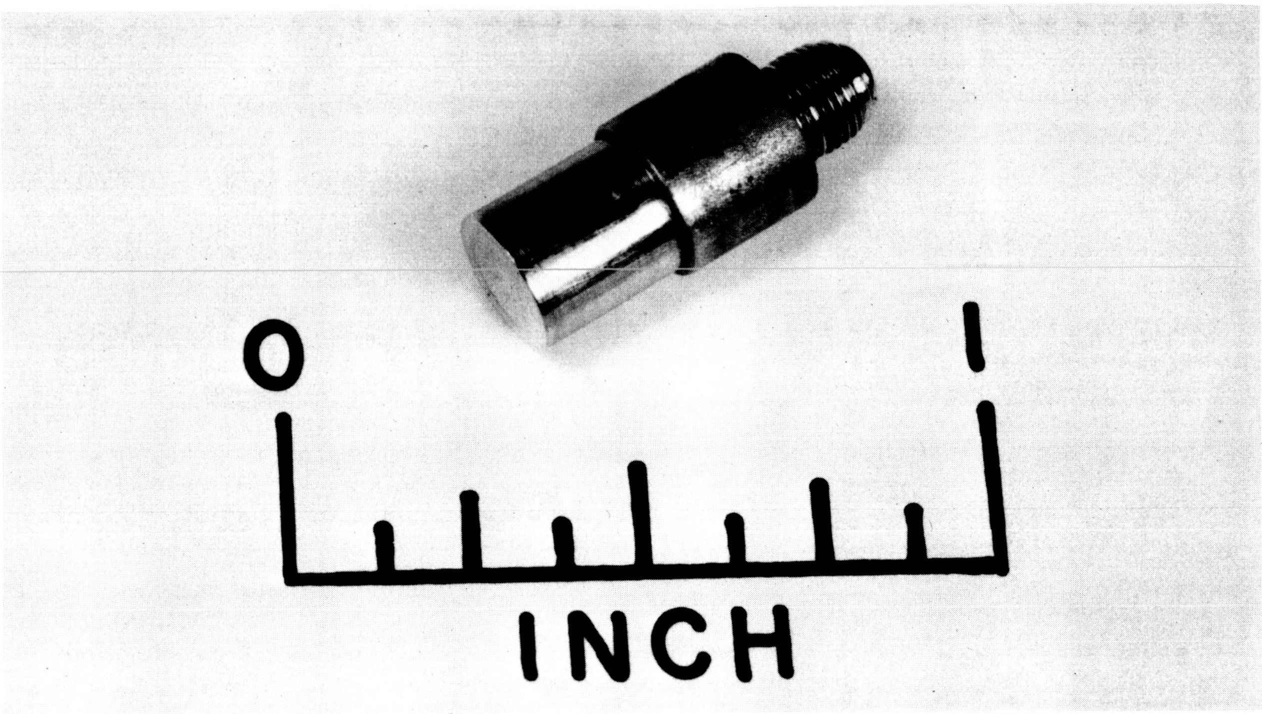
An effort to keep apace with the transient pressure measuring requirements in liquid propellant rocket thrust chambers was maintained throughout the research. Since progress in developing cooled flush diaphragm transducers which would meet the increasingly severe operating conditions under fully developed combustion instability was slow, attention was directed more and more to the evaluation of uncooled fast response transducers and methods of adapting them to research and high performance rocket thrust chambers.

1. Flush Diaphragm Transducers

a. Uncooled Transducers
(1) Piezoelectric (Quartz) Crystal Type
(a) Kistler Model 601A

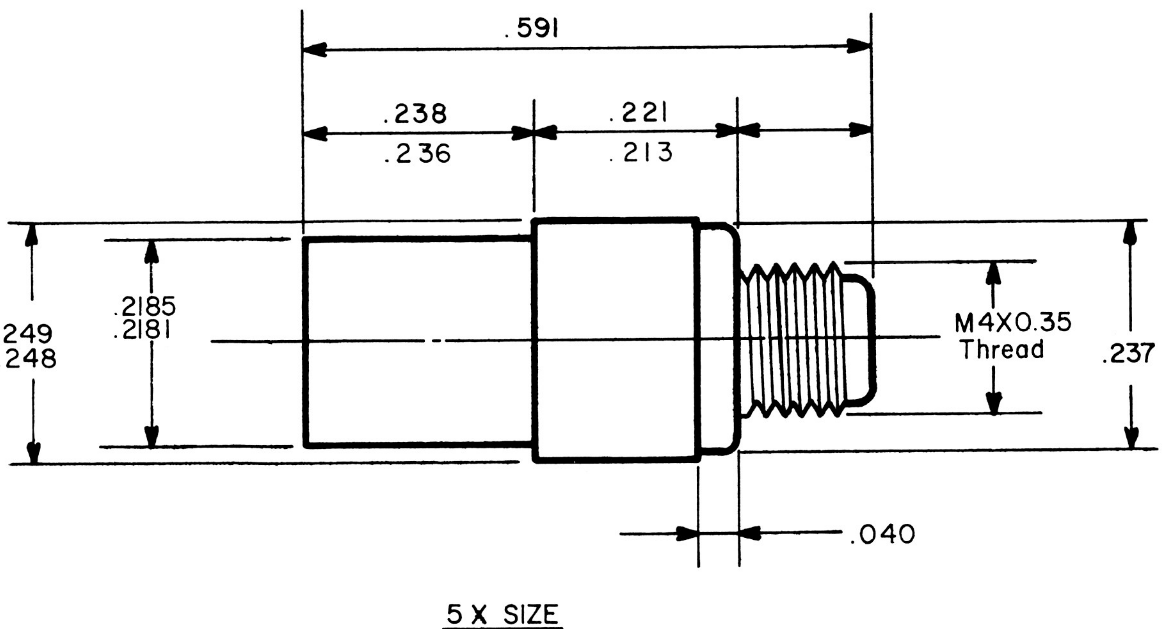
The Kistler Instrument Corporation Model 601A Miniature Quartz Transducer has a resonant frequency of about 140,000 Hz, a sensitivity of 1 pCb/psi and a pressure range to 3000 psi with a resolution of 0.1 psi. Used with the proper charge amplifier, output is in the order of volts. The miniature size of the transducer shown in Figures 1 and 2 permits installation without great disturbance to local structure. Adapters designed for the application of this uncooled unit to cooled and uncooled rocket thrust chambers are available and it has been used in the design of adapters for special applications.

In the past it has been almost impossible to achieve low zero drift (3) with quartz transducers so that steady state measurements could not be taken and calibration was difficult. The static calibration shown in Figure 3 and data from the Summary Evaluation Tables for Adapters employing



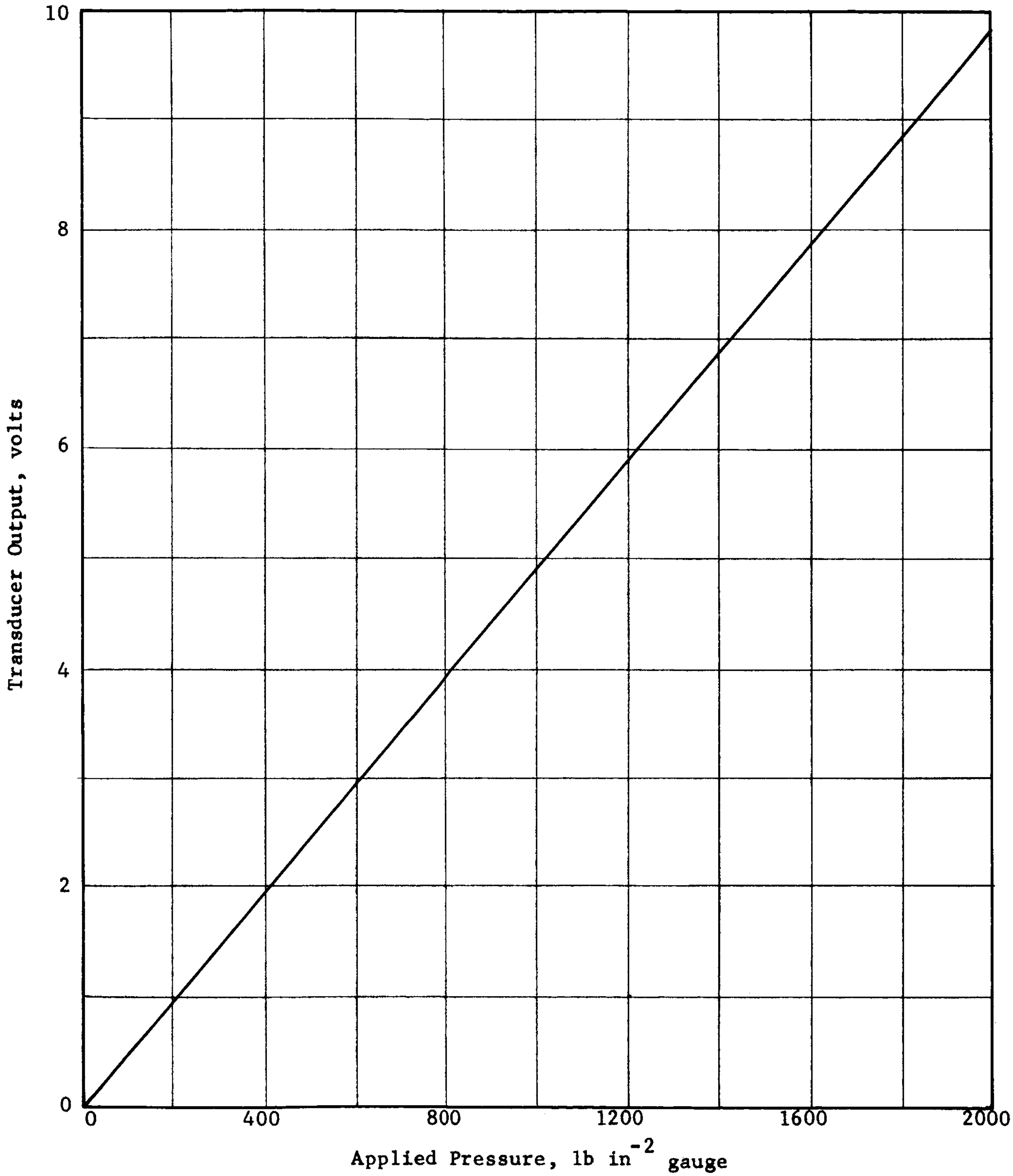
Photograph of Kistler Model 601A
Miniature Quartz Pressure Transducer

FIGURE 1



Drawing of Kistler Model 601A
Miniature Quartz Pressure Transducer

FIGURE 2



Transducer Output vs Applied Pressure
Kistler Model 601A Serial No. 5163

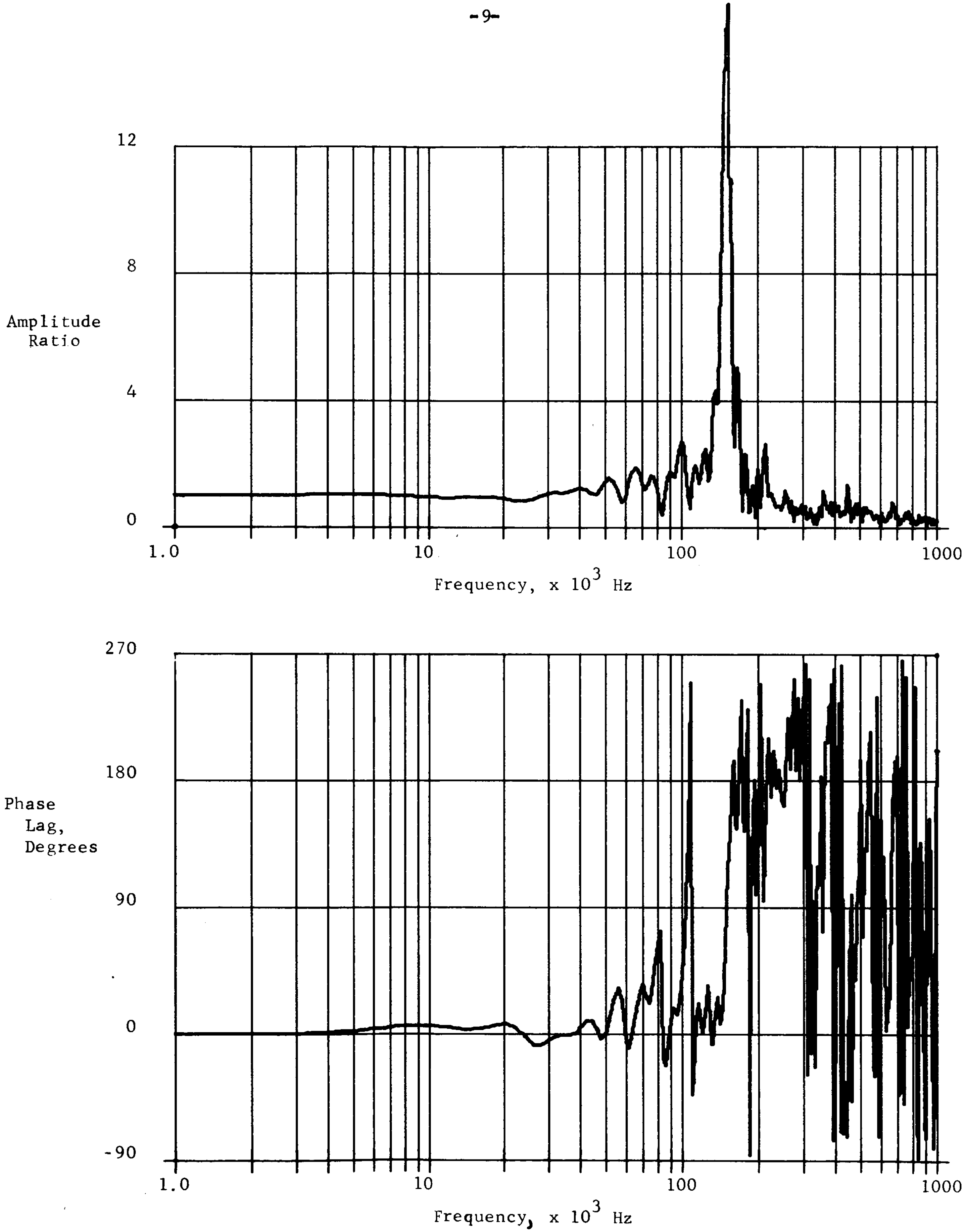
FIGURE 3

the Kistler 601A transducer, presented later in this Section, demonstrate the capability of this transducer for short term steady state pressure measurements when connections are properly cleaned and sealed.

Dynamic performance is demonstrated by the curves of Figure 4. The amplitude ratio and phase lag vs frequency were computed from shock tube data, using a computer program based on the straight-line approximation (4). Dynamic response of the 601A is seen to be flat to about 20 Hz. For this reason the monitoring transducer chosen for the Princeton Sinusoidal Pressure Generator remained a Kistler 601A throughout the research. In addition, because of its fast response and small size, the 601A was used as a shock tube evaluation instrument and an instrumentation triggering device in the shock tube during other transducer evaluations. It is believed to be an excellent general purpose test instrument when its use is understood and it is properly handled. The Kistler 601A and its derivative the 603A have been used successfully for very short duration combustion instability tests in uncooled rocket motors as described below in more detail.

(b) Kistler Model 603A

The Kistler Model 603A transducer is similar to the 601A but is acceleration compensated. Except for length of the 0.249 diameter retaining section (See Figure 2), the dimentions are identical to those of the Model 601A. A Kistler 105H connector adapter makes it interchangeable with the 601A. Acceleration compensation is accomplished by placing two quartz elements back to back within the transducer body, the second element cancelling out acceleration effects sensed by the first element. This structure reduces the sensitivity to about one-third that of the 601A or about 0.35 pCb per psi. However, when used with the proper amplifier, the system output is several volts (up to 10 volts using a Kistler Model 504



Dynamic Performance of Kistler Model 601-A Serial No. 4045

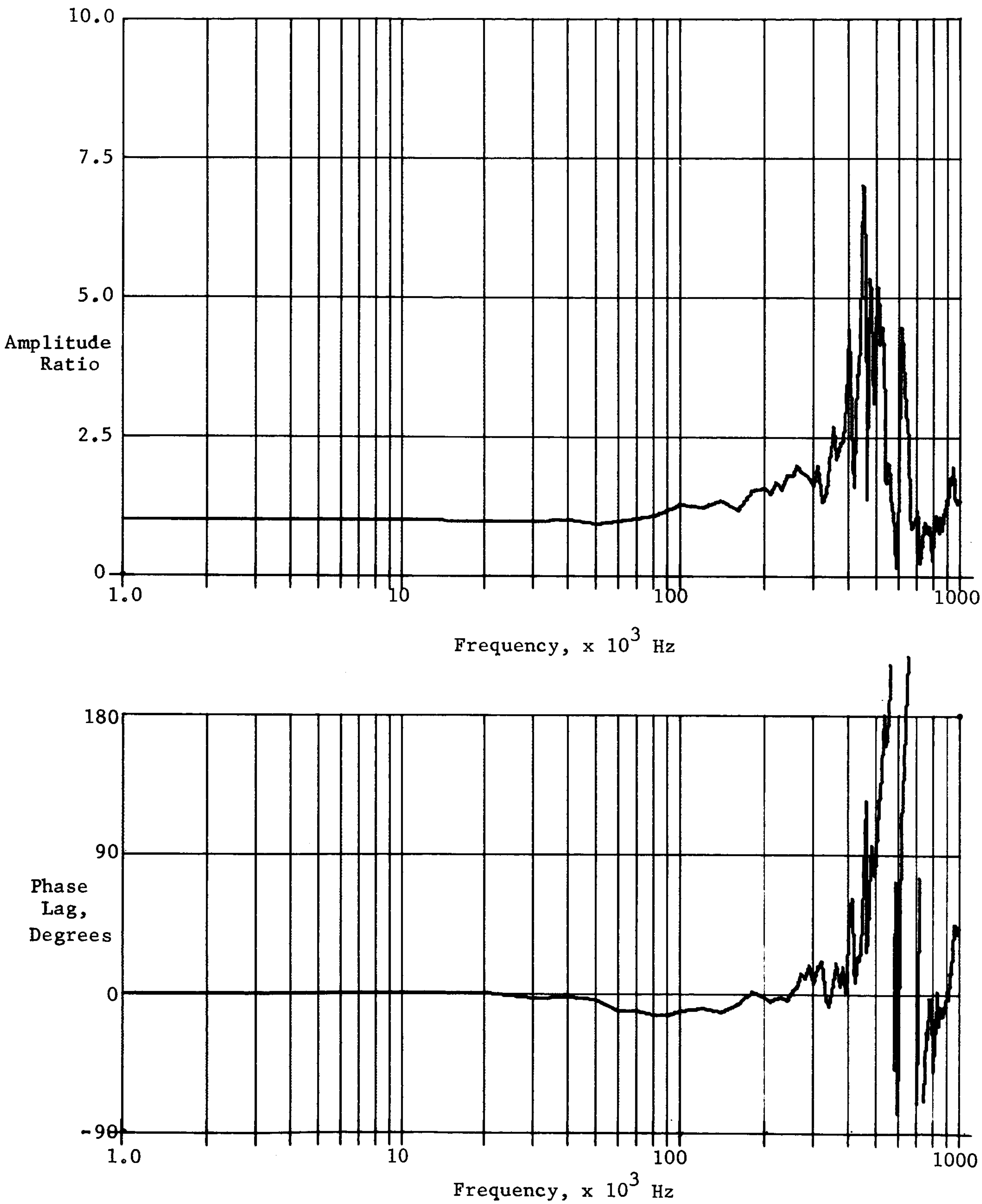
FIGURE 4

amplifier which has gain increments from 1 to 5000 psi per volt). This research terminated before the 603A was fully developed. Some additional performance specifications from the manufacturer are: pressure ranges to 3000 psi with 5000 psi on overload a resolution of 0.03 psi and resonant frequency greater than 400,000 Hz. The confirming dynamic performance shown in Figure 5 was computed from a shock tube photograph furnished by personnel of Jet Propulsion Laboratory Edwards Test Station. They have had considerable experience with these uncooled transducers on very short duration rocket combustion instability tests as recently spotted at the ICRPG 3rd Combustion Conference (5).

b. Cooled Transducers

(1) Bonded Wire Resistive Strain Gauge Bridge Type
(a) Dynisco Model PT49

The Dynisco Model PT49 was used almost exclusively for a number of years in making transient pressure measurements during the course of a continuing research on liquid propellant rocket combustion instability at Princeton. Several significant changes were made in the PT49 transducer construction during that time. At the inception of this research, the Model PT49 transducer was available and was chosen for evaluation and further development as a flush diaphragm water cooled transient pressure measuring instrument to be used in liquid propellant rocket thrust chambers. Natural frequency approached 20,000 Hz, sensitivity was 3 millivolts per volt excitation (i.e., standard output for this type of transducer) with pressure ranges to 2000 psi. Diaphragm materials were 17-7-ph and 17-4-ph stainless steel welded to a type 347 stainless steel body. The transducer has an 11/16 inch diameter on a reach of 1/2 inche beyond a 1-1/8 x 12 mounting thread. Coolant tubes were solidly mounted (silver brazed) into the



Dynamic Performance of Kistler Model 603A Serial No. 132

FIGURE 5

transducer body and the pressure sensing diaphragm was stitch-welded to the coolant maze ribbon. The large mounting thread was removed and the transducer was adapted to flange mounting for work at Princeton, where most of the rocket motor thrust chambers were fabricated of heavy wall copper incapable of supporting a large thread load at high chamber pressures. The frequent removal and installation in these thrust chambers was also a problem in the case of threaded mounting.

The Laboratory Evaluation Procedure of Appendix C was devised to evaluate the PT49 transducers in the laboratory and obtain information leading to further transducer development. This procedure and contact maintained with the manufacturer led to changes involving larger bore and flexible coolant tubes for easy repair when internal coolant leaks developed a smooth and continuous coolant spiral passage in the diaphragm area to relieve coolant pressure drop and remove coolant stagnation areas, diaphragm materials other than stainless steel, tests of means for attaching the diaphragm to the transducer body and a spiral coolant maze. The latter change was made to increase heat transfer capability and to give strength to withstand higher coolant pressures. A ruggedized upper transducer body was also provided by the manufacturer which concluded the development and culminated in the Model PT49CF transducer.

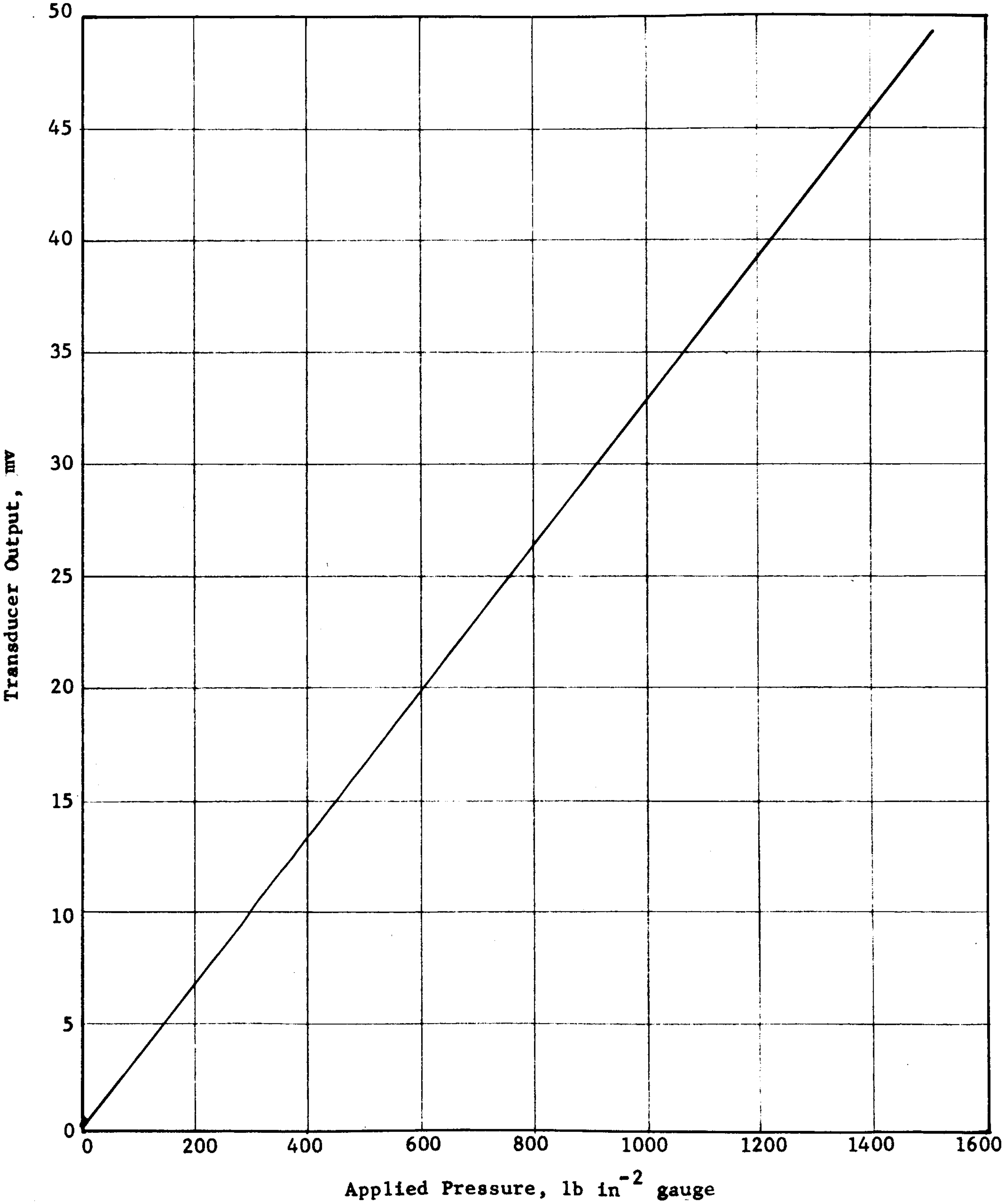
A prototype PT49CF transducer, Serial No. 20054, bearing a TD nickel diaphragm vacuum brazed to the newly designed coolant passage maze with gold-nickel brazing material, was evaluated and showed considerable improvement in average coolant pressure rating (from 75 to 175 psi) and a linearity never before realized in large diaphragm, bonded wire strain gauge transducers. The excellent linearity and nearly zero intercept of this instrument is displayed in the static calibration of Figure 6. Dynamic performance of instrument remained about the same as previous PT49 models.

Linearity, hysteresis, sensitivity and average coolant pressure rating remained nearly the same throughout development of the PT49CF Model. Natural frequency increased to 25,000 Hz and response to acceleration was reduced considerably. Nine Model PT49CF transducers were procured and evaluated, including the prototype transducer. Coolant tube and electrical failures characterized these transducers, but five transducers survived laboratory evaluation. The laboratory evaluation (Table I) and dynamic performance (Figure 7) presented here are typical of the PT49CF transducers. Evaluation of the PT49 is covered in more detail in Reference (2). Prior to the close of the research the Dynisco PT49 transducer had become obsolete and PT134 transducers designed to meet our target characteristics were procured as prototypes for evaluation.

(b) Dynisco Model PT134

The Dynisco Model PT134 transducer represented an effort to reduce the physical size of the four-arm bonded resistance wire strain gauge transducer and provide other advanced characteristics that had been previously published as target characteristics (6). The desired transducer was to have a diaphragm diameter of 1/4 inch (with a maximum of 3/8 inch) and a 3/4 inch nominal reach beyond a 1/2 x 20 mounting thread; however, the PT134 transducer had a 1/2 inch diameter (with a 3/4 x 16 mounting thread) which the manufacturer believed to be the minimum practicable.

Six prototype instruments were procured and evaluated. Three had a pressure range of 0 to 750 psi and three were in the 0 to 1500 psi range. Four of the six transducers survived laboratory evaluation with



Transducer Output vs Applied Pressure
Dynisco Model PT49CF-1M Serial No. 20054

FIGURE 6

TABLE I

Transducer Summary Laboratory Evaluation

Manufacturer: Dynisco, Division of American Brake Shoe

Model: PT49CF Serial: 21208 Measurand: Gage Pressure

Pressure Range: 0-2000 Temperature Range: ________

Transduction Method: Bonded Resistance Wire Strain Gage Bridge

Dimensions: Length 3.0 in. Width 1.5 in. Height 2.5 in. See Attached Dwg.

Weight 0.50 lbs.

Electrical Measurements: Resistance across Input 351.6 ohms

Resistance across Output 350.4 ohms

Resistance to Ground 5×10^8 ohms

Excitation: 10 V-dc Other Electrical Data: Mating Connector Cannon MC11E-10-65N

Coolant Conditions: Average Pressure 175 lb in^{-2} gage Water Flow 0.125 lb sec^{-1}

Other Coolant Data: Inlet tube specified. 7% flow increase when reversed.

STATIC PERFORMANCE

Without Coolant		With Coolant
30 millivolts	Full Scale Output	30 millivolts
0.015 mv/psi	Sensitivity	0.015 mv
0.52 mv	Zero Output	0.42 mv
0.07 mv	Maximum Deviation in Output from Computed Straight Line	0.13 mv
--	Drift Rate at Zero Pressure	0.015 millivolts/hr.

Coolant Temperature Rise per Unit Heat Flux: 3.16° F.

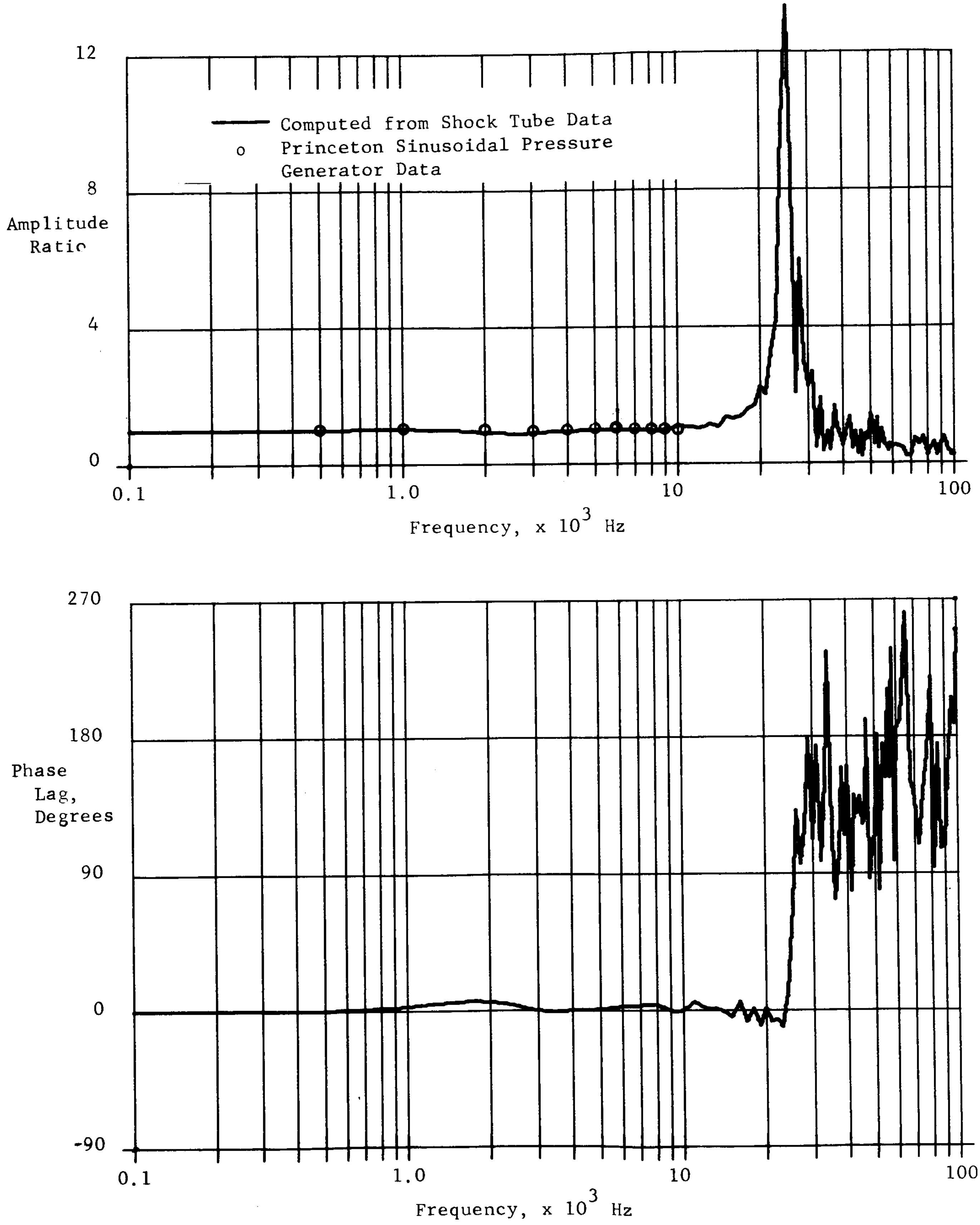
DYNAMIC PERFORMANCE

Resonant Frequency 25000 Hertz. See Attached Response Curves xx

Amplitude Ratio, Flat to within ± 10 percent up to 10, 000 Hz

COMMENTS

Initial and Date J.P.T.



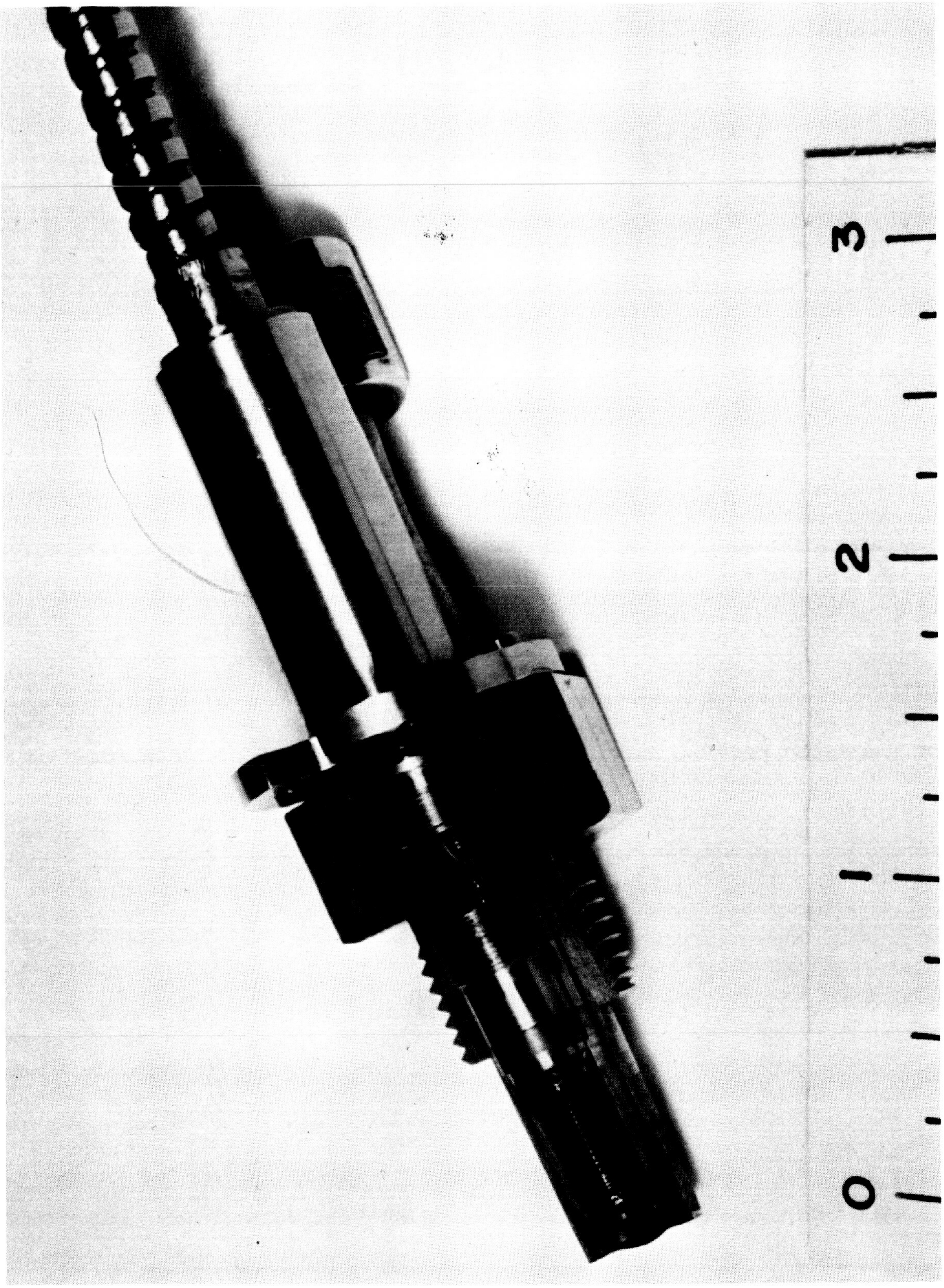
Dynamic Performance of Dynisco Model PT-49CF-2M Serial No. 21208

FIGURE 7

one electrical failure and another was tested to destruction in a coolant pressure test (2). Due to a large shift in the coolant pressure drop vs coolant flow with increased average coolant pressure, coolant flow was established at 0.08 lb sec^{-1} at an average coolant pressure of 275 lb in^{-2} gauge. Modifications to the PT134 during the course of evaluation included changing to armored cables and sealed connectors and a change in coolant maze configuration in the center of the diaphragm area to provide a more streamlined flow in this critical heat transfer area. The final version is shown in section photographically in Figure 8.

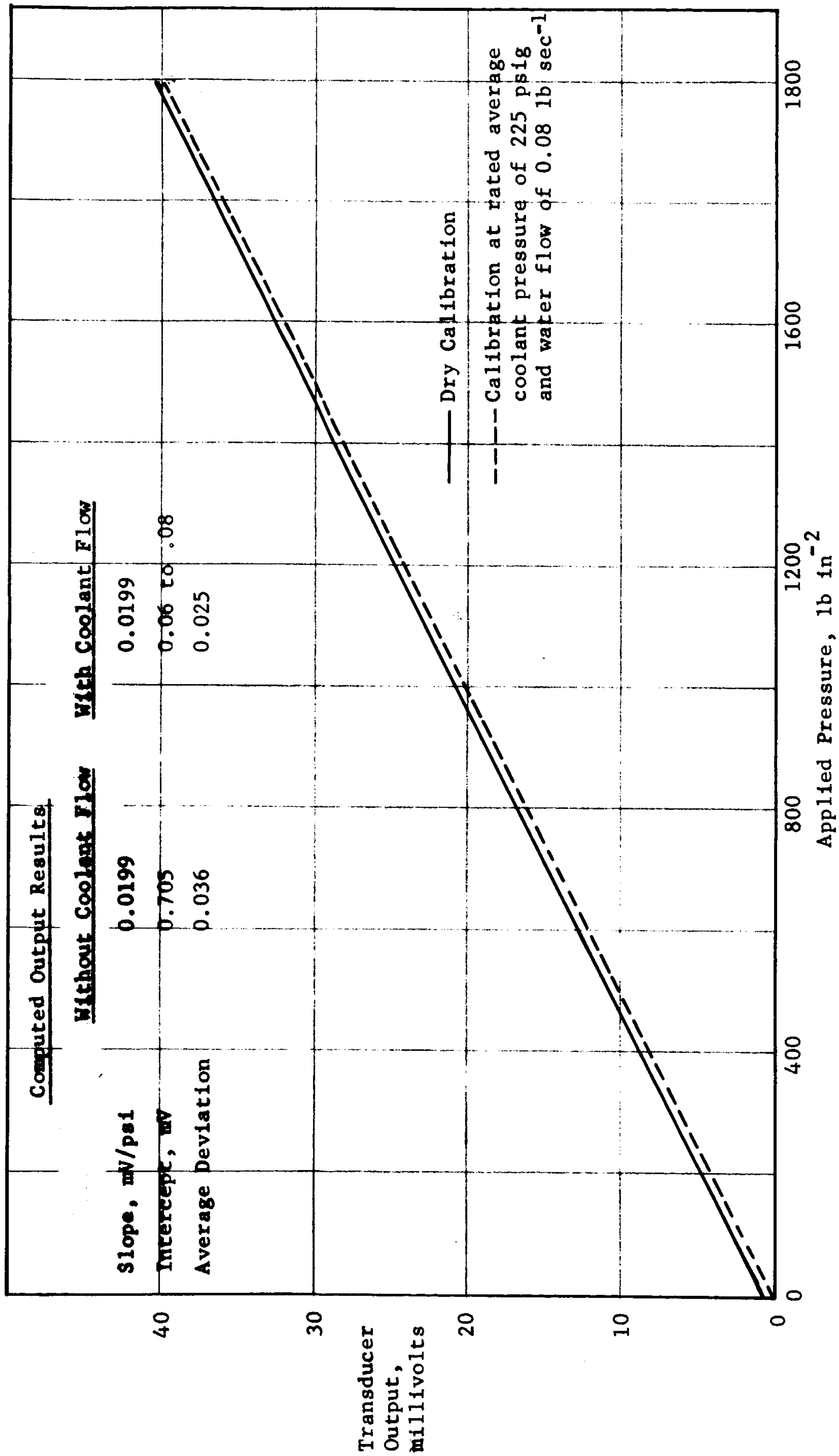
A difference in diaphragm construction between the prototype PT134 and the Model PT49C transducers was in the brazing material used to secure the diaphragm to the coolant maze ribbon. A high silver content, litho-braze alloy was selected finally by the manufacturer. Although this method of fastening survived laboratory testing, it succumbed to the harsh heating conditions of rocket testing. Close inspection of Figure 8 shows the diaphragm separated from the maze ribbon. A return to the nickel-gold brazing alloy used in the PT49C construction or, preferably, electron beam welding would seem to be indicated. Figure 9 shows a typical plot of PT134 output vs applied pressure with excellent linearity; however, a shift in zero with coolant pressure is shown to exist.

Heat transfer capability of the basic PT134 configuration remains to be determined. Compared with low heat flux data gathered with the model PT49C in similar environments, where coolant temperature rise per unit heat flux amounted to 3.2 degrees Fahrenheit, the PT134 indicated a 2.5 F coolant temperature rise. Later rocket runs were made with a 0.060 in coating of General Electric RTU-580 silicone compound over the diaphragm



Sectioned Dynisco Model PT134-2M Water Cooled,
Flush Diaphragm Transient Pressure Transducer

FIGURE 8



Transducer Output vs Applied Pressure
Dynisco Model PT134-1.5M Serial No. 22121

FIGURE 9

did not deteriorate the dynamic performance appreciably but resulted in a two-thirds reduction (typically 18.5 to 6.2 Btu in^{-2} s^{-1}) of heat flux to the transducer under combustion instability conditions.

Laboratory tests, in which transducer environment was controlled, indicated that a large part of the total recorded heat flux resulted from lateral heat flow or heat transferred through the transducer body. Lateral heat flux values ranged from 12 to 43 percent of the total recorded heat flux in over 40 laboratory tests using the PT134 transducer (8).

The Summary Laboratory Evaluation (Table II) and dynamic performance curves (Figure 10) included here are typical of the five transducers (except for pressure range) that passed through the laboratory. Resonant frequency was greatly improved over the Model PT49C and ranged from 35,000 to 40,000 Hz.

(2) Capacitance Type

(a) Photocon Model 532A-4925

The Photocon Model 352A-4925 transducer, shown in Figure 11, was selected for its high output, type of transduction and the special cooled copper flame shield. The instrument has seen wide use especially by Rocketdyne and in the Aerojet-General Corporation GEMSIP Program (11).

A Summary Laboratory Evaluation is presented in Table III and dynamic performance with a shock input is seen in Figure 12. Except for a long warmup time, required for zero stabilization and a small residual drift, static performance was excellent.

Dynamic performance (refer to Figure 12) in the shock tube shows a primary assembly resonance of approximately 12,500 Hz with very low amplitudes. Amplitude ratio as determined in the sinusoidal pressure generator was flat (± 10%) to 10,000 Hz except at 5000 Hz where a ratio

TABLE II

Transducer Summary Laboratory Evaluation

Manufacturer: Dynisco, Division of American Brake Shoe

Model: PT134 Serial: 22121 Measurand: Gage Pressure

Pressure Range: 0 - 1500 psig Temperature Range: ____

Transduction Method: Bonded Resistance Wire Strain Gage Bridge

Dimensions: Length 3.5 in. Width 1.3 in. Height 1.3 in. See Attached Dwg.

Weight 0.5 lbs.

Electrical Measurements: Resistance across Input 362 ohms

Resistance across Output 330 ohms

Resistance to Ground ∞ ohms

Excitation: 10 V-dc Other Electrical Data: ____

Coolant Conditions: Average Pressure 225 lb in^{-2} gage Water Flow 0.08 lb sec^{-1}

Other Coolant Data: ____

STATIC PERFORMANCE

Without Coolant		With Coolant
29.87 mv	Full Scale Output	29.85 mv
0.0199 mv/psi	Sensitivity	0.0199 mv/psi
0.65 mv	Zero Output	0.08 mv
0.037 mv	Maximum Deviation in Output from Computed Straight Line	0.16 mv
	Drift Rate at Zero Pressure	-0.02 mv/hr.

Coolant Temperature Rise per Unit Heat Flux: 2.46° F.

DYNAMIC PERFORMANCE

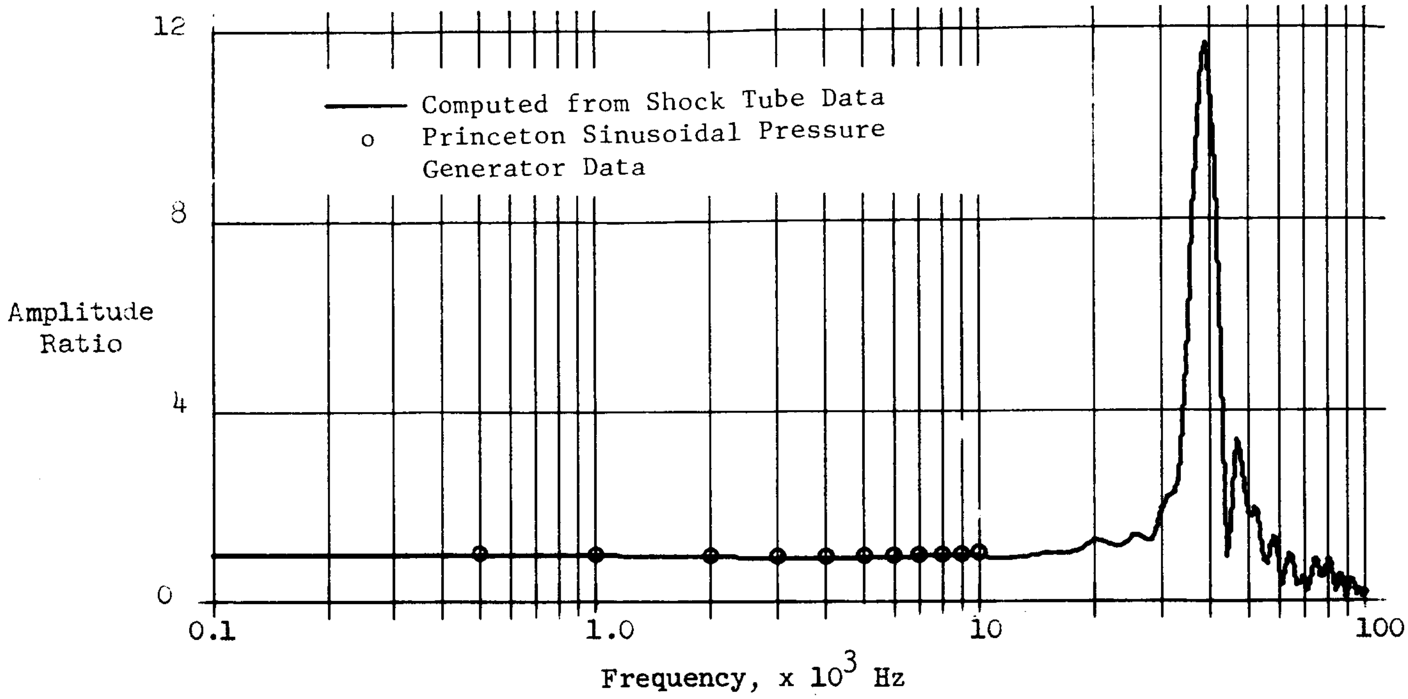
Resonant Frequency 39000 Hertz. See Attached Response Curves xx

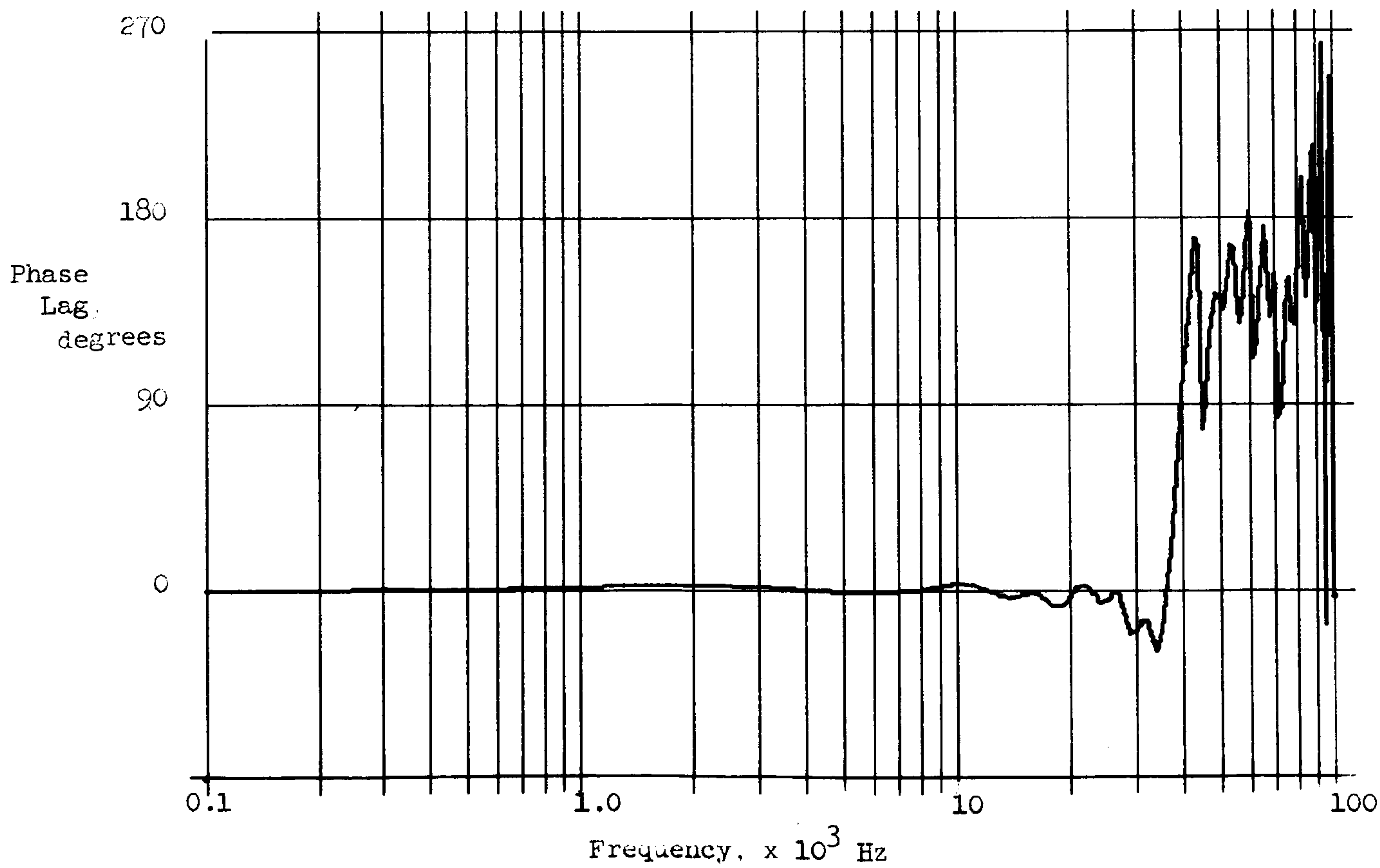
Amplitude Ratio, Flat (± 10 percent) up to 10,000 Hz

COMMENTS

____

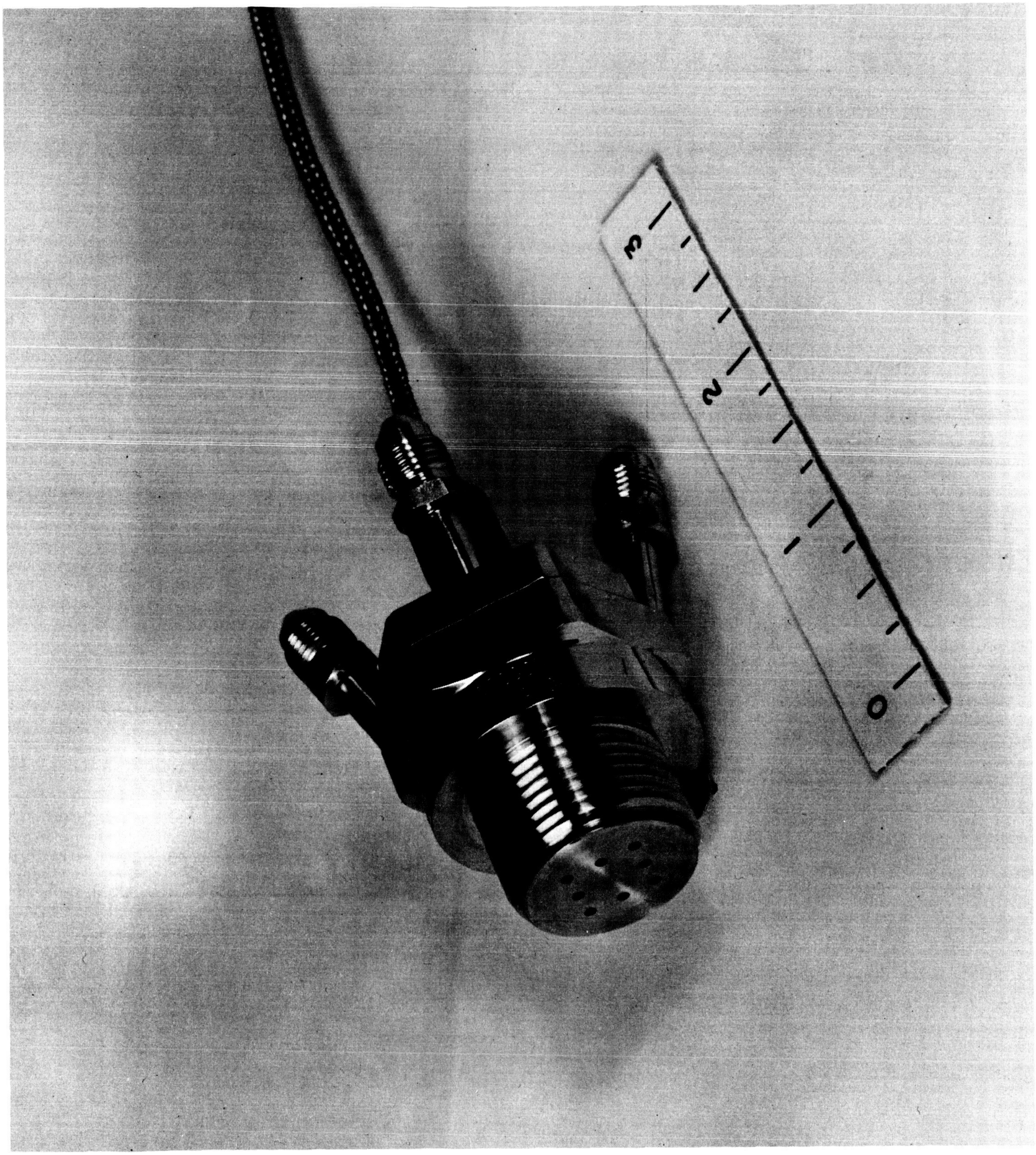
Initial and Date ____





Dynamic Performance of Dynisco Model PT134-1.5M Serial No. 22121

FIGURE 10



Photocon Research Products Model 352A-4925
Transducer with Flame Shield

FIGURE 11

TABLE III

Transducer Summary Laboratory Evaluation

Manufacturer: Photocon Research Products

Model: 352A-4925 Serial: 7841 Measurand: ______

Pressure Range: 0-2000 psig Temperature Range: ______

Transduction Method: Capacitance

Dimensions: Length 2.5 in. Width 2 in. Height 1.75 in. See Attached Dwg.

Weight 0.5 75 lbs.

Electrical Measurements: Resistance across Input ______ ohms

Resistance across Output ______ ohms

Resistance to Ground ______ ohms

Excitation: ______ Other Electrical Data: Photocon Power Supply and Dynagage Model 605 used for evaluation

Coolant Conditions: Average Pressure 35 lb in^{-2} gage Water Flow 0.08 lb sec^{-1}

Other Coolant Data: Average Pressure in Shield = 300 psig. Flow = 0.172 lb sec^{-1}

STATIC PERFORMANCE

Without Coolant		With Coolant
10.64 volts	Full Scale Output	10.60 Volts
5.32 MV/psi	Sensitivity	5.3 MV/psi
	Zero Output(adjustable)	0
45 MV	Maximum Deviation in Output from Computed Straight Line	84 MV
	Drift Rate at Zero Pressure	0.045 Volts/hr.

Coolant Temperature Rise per Unit Heat Flux: 1.25 (Transducer)

DYNAMIC PERFORMANCE

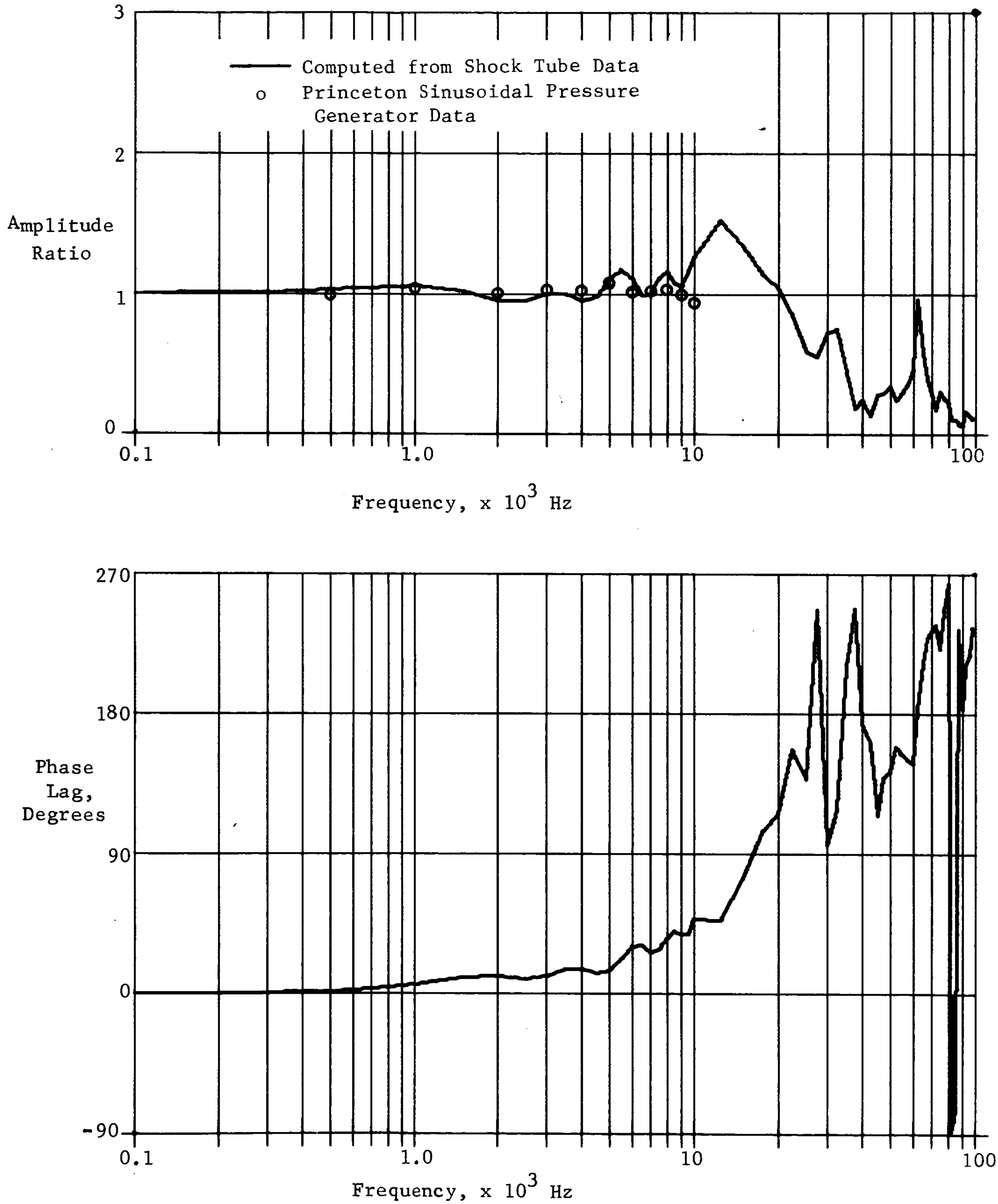
Resonant Frequency 12,500 Hertz. See Attached Response Curves

Amplitude Ratio, Flat to within ±10 percent up to 9,000 Hz

COMMENTS

Response data to step input unable to be analyzed currently due to low amplitude of oscillations and type of damping.

Initial and Date J.P.T.



Dynamic Performance of Photocon Model 352A-4925 Serial No. 7841

FIGURE 12

of 1.13 was obtained and a ratio of 0.84 indicated some attenuation at 10,000 Hz.

The rocket motor test data of Figure 13 shows a thermal drift in steady state data at a heat flux of 3.2 Btu in^{-2} sec^{-1}, as determined by the monitoring Dynisco PT49CF transducer. Coolant flow in both transducer and flame shield was the maximum obtainable from coolant pressure set by the manufacturer. Response to transient pressure was excellent.

(3) Piezoresistive Semi-Conductor Strain Gauge Bridge Type

(a) Electro-Optical Systems Model PT15C-2

A Model PT15C-2 transducer, designed for cryogenic spray cooling of the diaphragm was evaluated within the limits of the laboratory equipment both at room temperature and liquid nitrogen temperature. The transduction method, which utilizes miniature silicon strain elements, allows a flush diaphragm transducer of variable reach to be produced. The PT15C-2 has diaphragm diameter of 0.0625 inches, a coolant tube or frontal diameter of 0.150 inches and reach of 2.25 inches, which was 1.45 inches beyond a 10-32 mounting thread. Maximum allowable torque on the 10-32 thread was 10 in-lb. This provided sufficient gasket loading in the warm condition but at liquid nitrogen temperatures considerable difficulty was experienced in obtaining a seal. A gasket made up of 1/32 inch thick Kel-A material centered in a fully-annealed copper washer 0.026 inches thick provided an excellent seal to 1.33 times rated transducer pressure at -320°F during the shock tube tests.

Transducer zero stability was excellent for both cold and warm conditions although some excursion of output signal occurred on cool down. At constant temperature the transducer always returned to its normal zero

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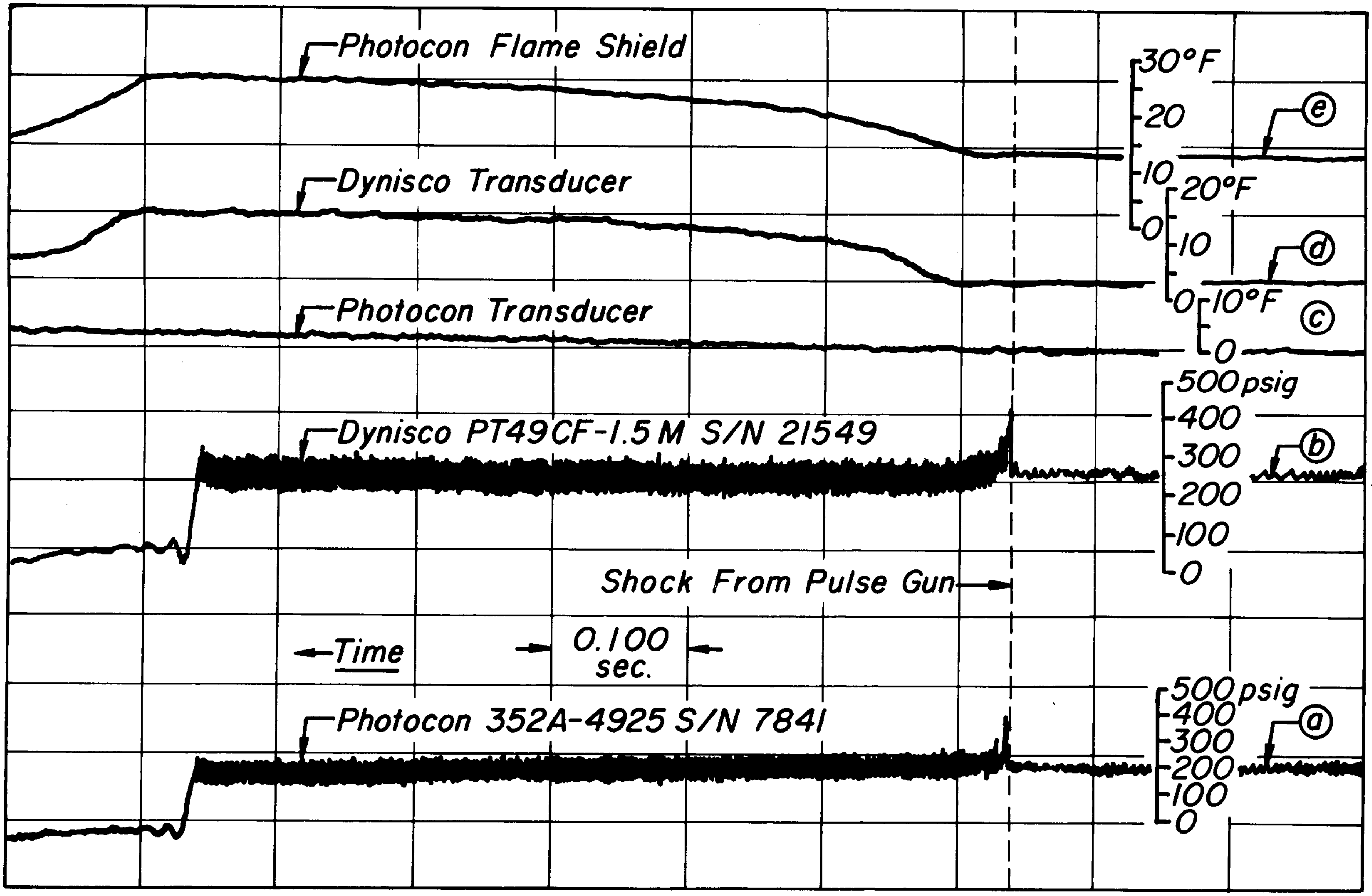


Rocket Motor Performance Data, Photocon Model 352A-4925
Compared with Dynisco Model PT49CF-1.5M

FIGURE 13

output. Sensitivity given as the slope of a computed best fit straight line from a 42 point calibration to 1950 lb in^{-2} gauge and at 10 milliamps constant current supply, was 0.0575 millivolts/lb in^{-2}. Hysteresis was negligible and average deviation in output from the computer straight line was 0.68 millivolts.

Extended efforts to test this transducer in the shock tube with liquid nitrogen in place of liquid hydrogen as the coolant were not successful.

No deviation from unity occurred in amplitude ratio vs frequency up to 10,000 Hz as determined in the Sinusoidal Pressure Genrator in the warm condition.

Rocket testing with liquid hydrogen using a tank provided by the Lewis Research Center was scheduled but was not run as the tankage did not meet the requirements of the New Jersey State Code for Pressure Vessels and an exception could not be obtained.

(b) Photocon Model 5000 Series

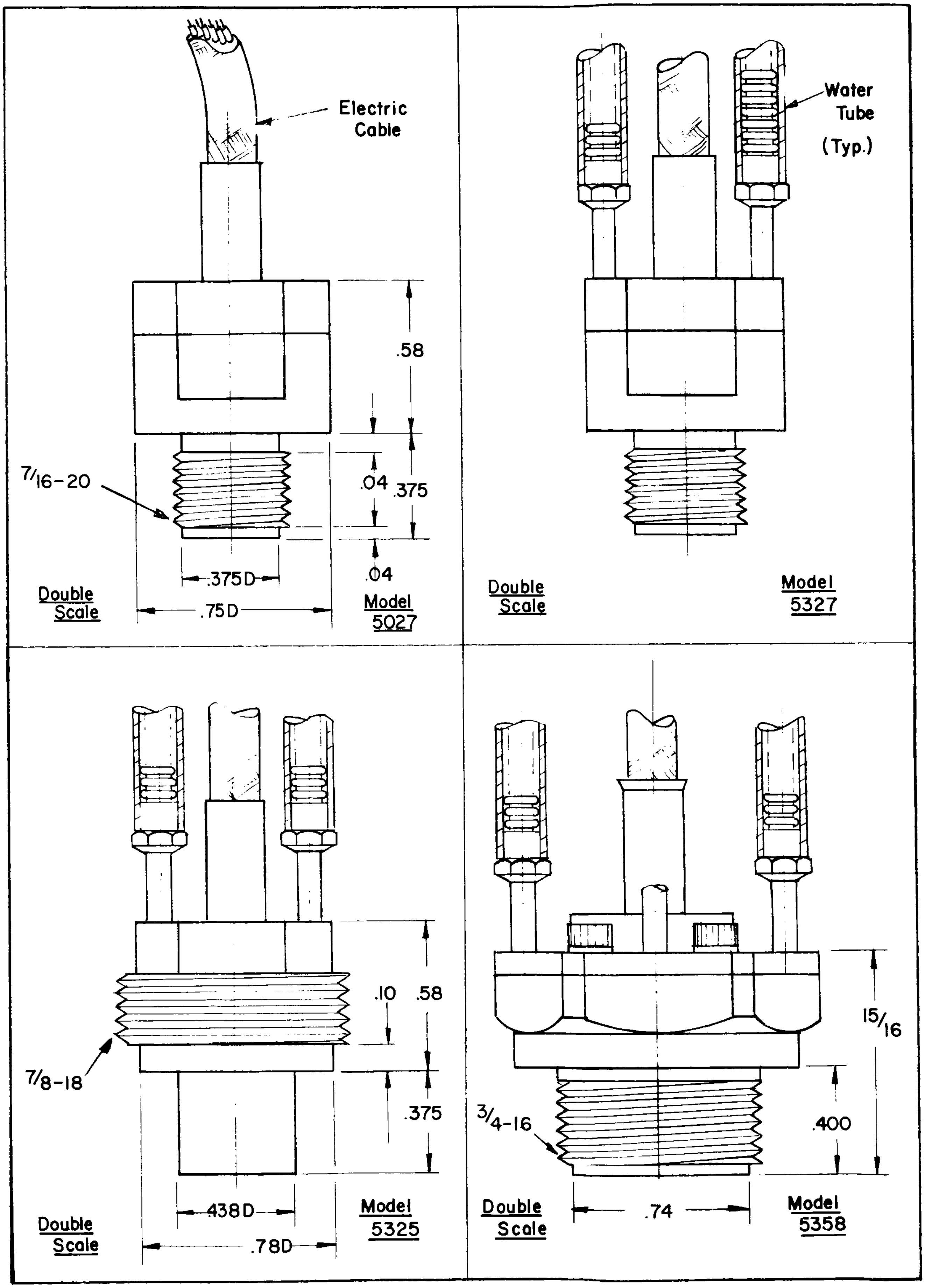
The Photocon 5000 Series semi-conductor strain gauge bridge transducers are designed to measure static and dynamic pressures under a wide range of conditions associated with rocket and jet propulsion studies and other similar applications. Although this model series appeared too late for evaluation, they represent in various models a serious effort by a quality manufacturer to develop a line of transducers to meet many of the needs identified during the course of this research. The transducers are available for anumber of pressure ranges from 250 to 5000 psig full scale and the output is 375 millivolts for a constant voltage bridge excitation of 10 volts direct current. Models for high temperatures and cryogenic, as well as uncooled, applications are available. Several geometries, including flame shielded versions are included as shown on Figure 14. Model 5027 is an uncooled version and Model 5327 is a cooled version of the basic configuration that has a 3/8 inch diameter diaphragm at the end of a threaded section of equivalent length. The Model 5325 is a slightly enlarged cooled version with 7/8 inch threads on the body and a 3/8 inch cylindrical spout with a 0.438 inch diameter diaphragm at the end of it. Model 5358 is a flame shielded version similar in configuration to the Model 352A described above. Model 2000 and 3000 series of these transducers with constant current excitation are also available. While no evaluation of these model series of transducers was undertaken the undertaking is to be applauded and their further development fostered.

2. Piston Transducers

a. Piezoresistive Semi-Conductor Strain Gauge Bridge Type

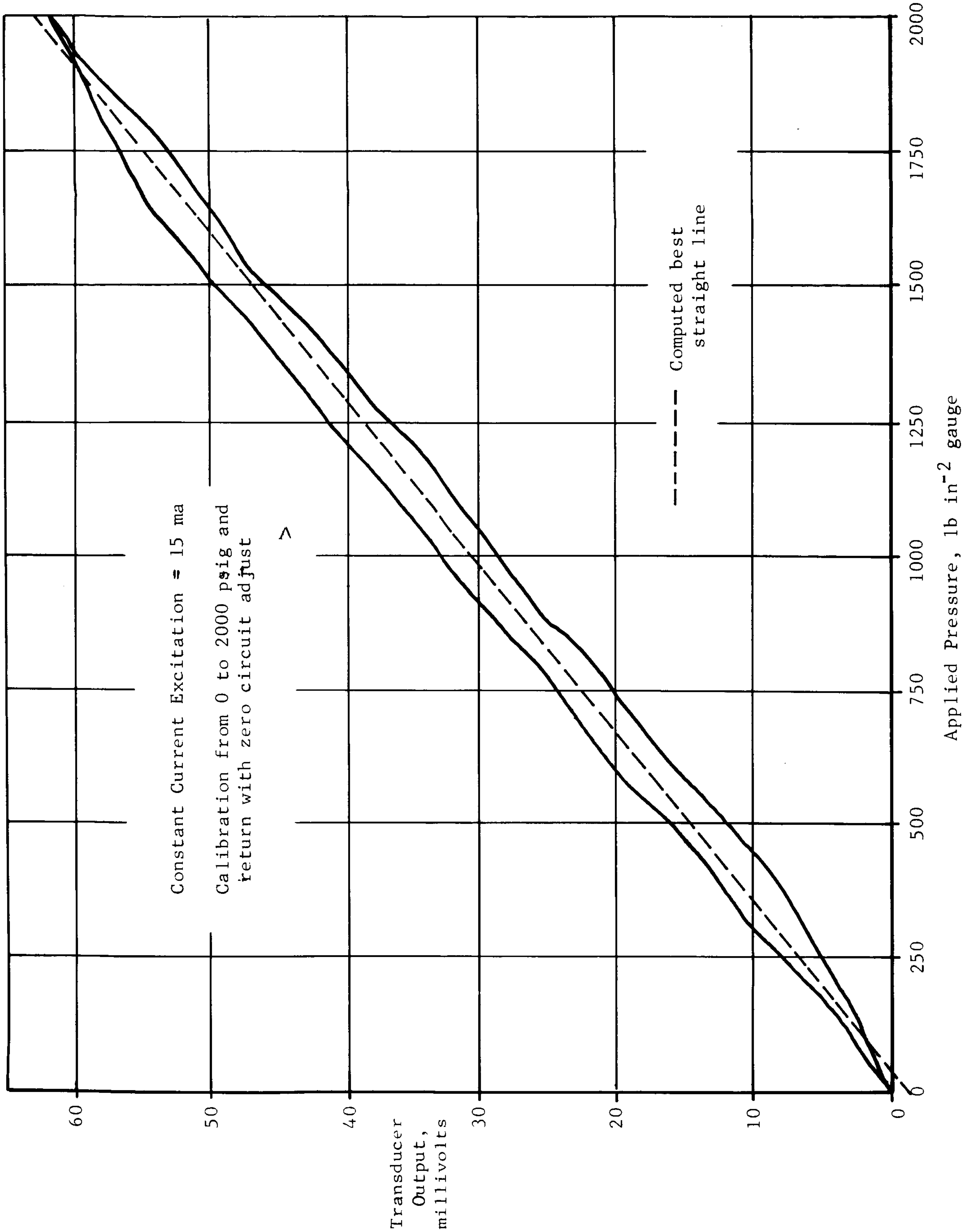
(1) Photocon Model 200

Silicon semi-conductor strain elements, bonded to a reduced square section of 1/8 inch diameter piston, are employed in the PRP-200 as a method of strain bridge type of transduction. The merits of silicon semi-conductor strain bridge transduction, the gage factors much higher than bonded wire strain bridges and construction of small transducers, are well known. Although small in size and apparently rugged enough to withstand most of the harsh treatment encountered in rocket thrust chambers, the good dynamic response available from this type of transduction has been sacrificed. A large amount of hysteresis has also been introduced and application of static pressure calibrations to transient data reduction is doubtful. Laboratory evaluation results are presented in the static calibration of Figure 15 the shock tube photos of Figure 16 and the Amplitude Ratio vs Frequency Curve of Figure 17.



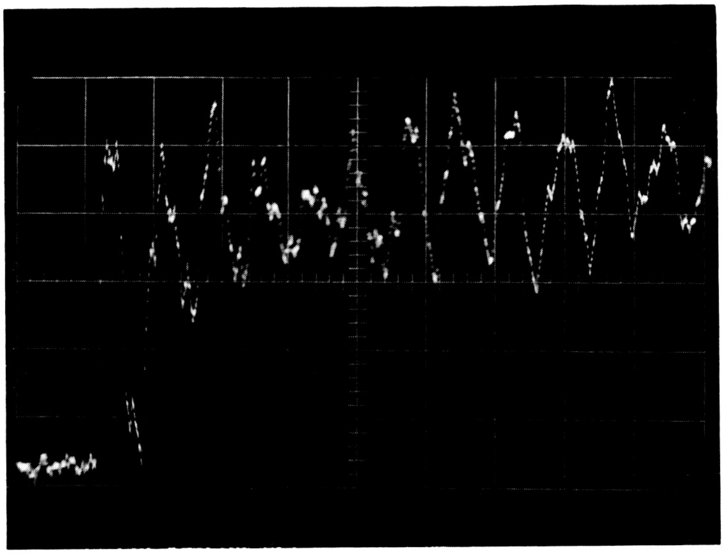
Drawings of Photocon Models 5027, 5325, 5327 and 5358

FIGURE 14



Transducer Output vs Applied Pressure Photocon Model 200 Serial No. 107

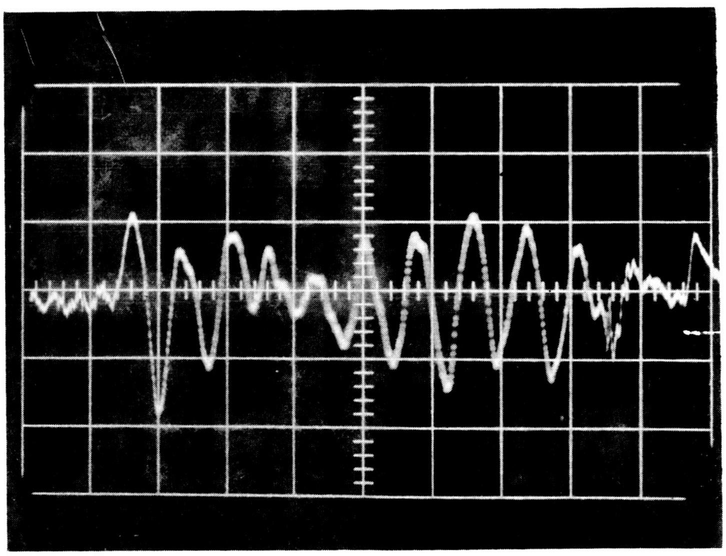
FIGURE 15



A. Active Shock Tube Test

Vert Sensitivity $\underline{3.5\ \text{mv cm}^{-1}}$

Sweep Rate $\underline{50\ \text{microsec cm}^{-1}}$



B. Acceleration Test with

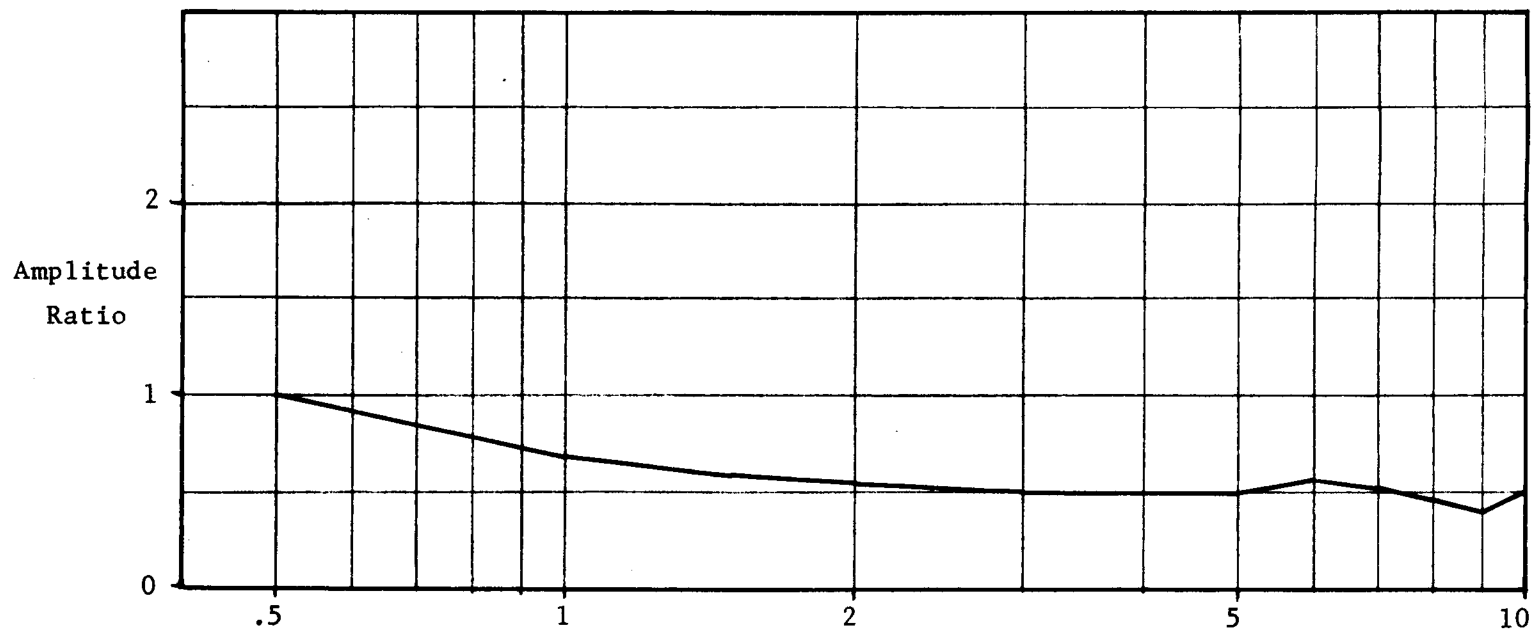
Shock Tube Blank Installed

Vert Sensitivity $\underline{3.5\ \text{mc cm}^{-1}}$

Sweep Rate $\underline{50\ \text{microsec cm}^{-1}}$

Dynamic Response to Shock Input
Photocon Model 200 Serial No. 107

FIGURE 16



Amplitude Ratio vs Frequency from Princeton Sinusoidal Pressure Generator
for Photocon Model 200 Serial No. 107

FIGURE 17

Peak-to-peak oscillations equal to about one half the pressure step and at approximately 26,700 Hz are displayed in the shock tube data. Acceleration shots, in which the transducer is blanked off by a steel plate, display the same frequency at about the same amplitude. This ringing is undoubtedly mechanical. Very high amplitudes at 5000 Hz and still significant amplitudes at 100,000 Hz also appear in the shock tube data. Oscillations of small magnitude also occur at about 500,000 Hz. The disagreement between the response curve generated from Sinusoidal Pressure Generator data, which shows a 50 percent attenuation, the high amplitude ringing in the shock tube data and growing amplitude with time in the rocket test traces of Figure 18 remain largely unexplained.

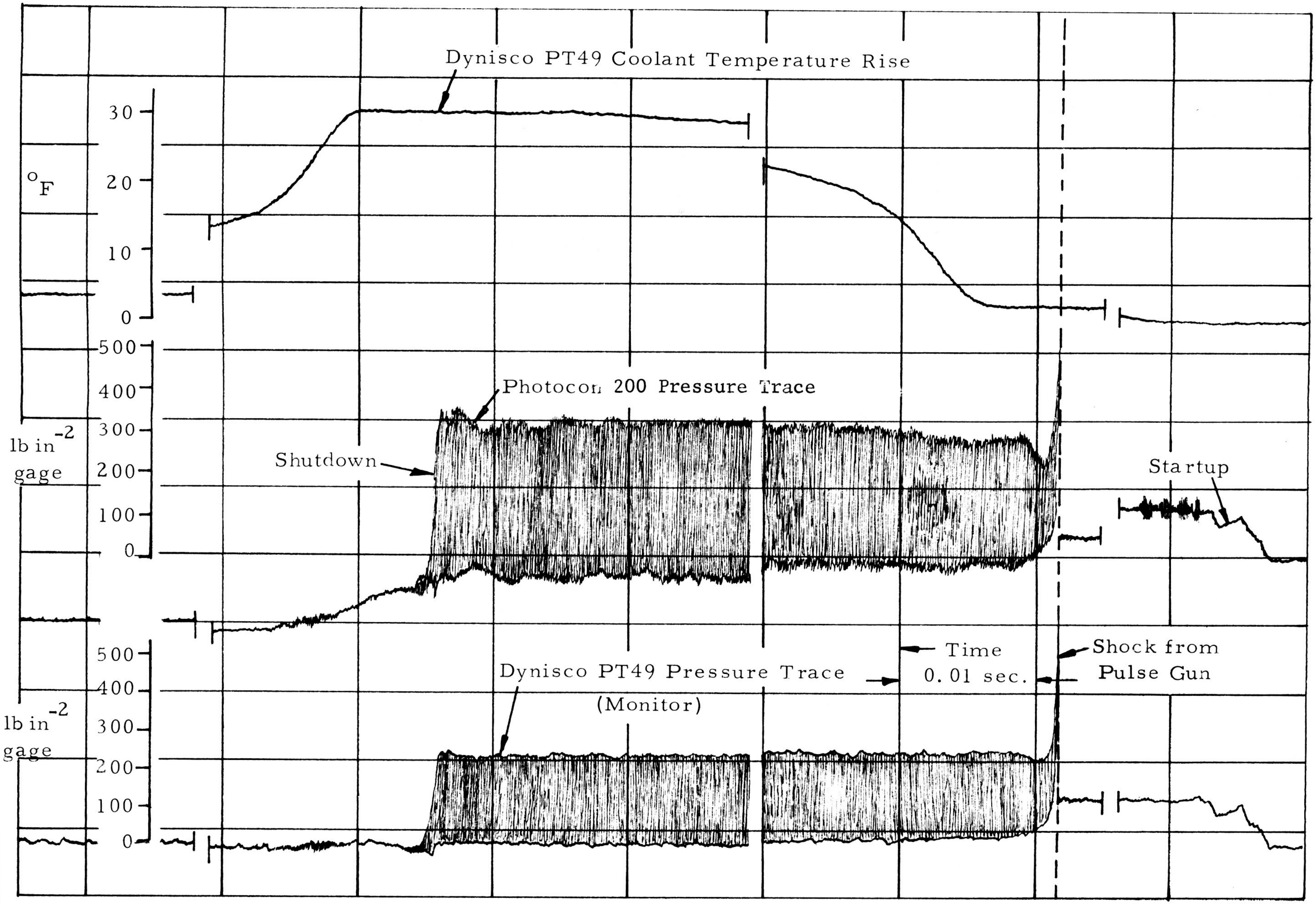
3. Passage Connected Transducers

a. Short Passage Connected Transducers

(1) Kistler Model 616A

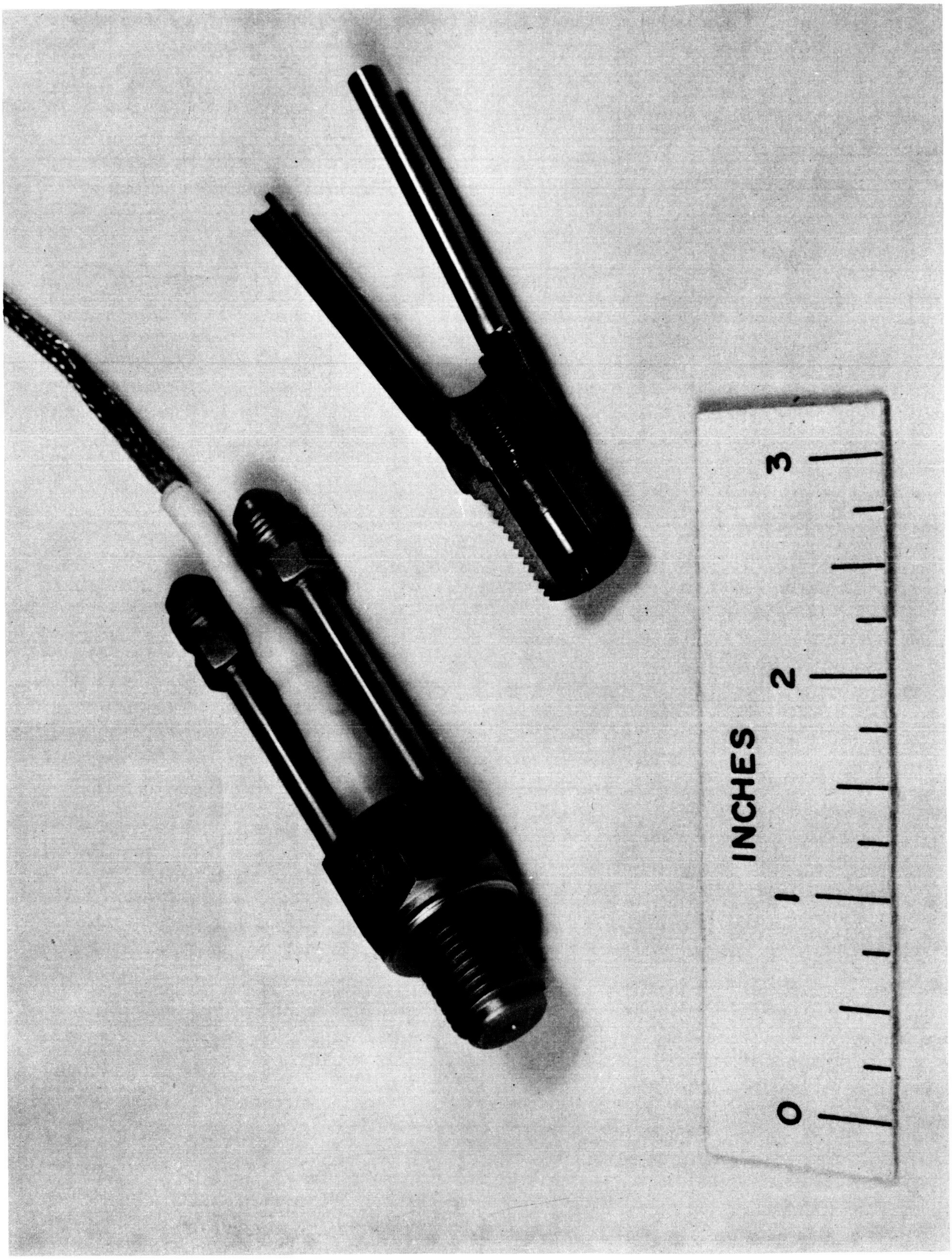
The Kistler Model 616A of Figure 19 is a water-cooled adapter (coolant passages shown in the section) which houses a Model 601A transducer. The transducer diaphragm is located at the end of a very short passage which is 1/10 inch long and approximately 1/16 the transducer diaphragm area. Although this cooled adapter provides excellent protection for the transducer body and serves well during steady combustion, the transducer diaphragm is virtually unprotected during the pumping action of fully developed combustion instability. Considerable success in unstable rocket motor test operations elsewhere has been reported; however, where the transducer diaphragm is coated with ablative rubber (G.E. RYV compunds).

The amplitude ratio vs frequency curve from the Princeton Sinusoidal Pressure Generator was flat (± 10%) through 9000 Hz and the shock tube data showed the response to be ragged above that frequency. The



Oscillograph Traces of Photocon Model 200 Serial No. 107
vs Dynisco Model PT49 Serial No. 21197 for Rocket Motor Test No. A1183

FIGURE 18



Photograph of Kistler Model 616A Passage Connected Transducer

FIGURE 19

The Summary Evaluation (Table IV) and dynamic response curves (Figure 20) are provided.

b. The Princeton Small Passage Gas Bleed Technique

The long-term development of cooled flush diaphragm transducers to withstand heat flux inputs of 25 Btu in^{-2} sec^{-1} and the poor system dynamic response due to size when these instruments were passage connected, drew attention to the small uncooled fast response piezoelectric transducers and the possibility of passage connecting them and maintaining a good system dynamic response. Research in this area resulted in the Princeton Small Passage Helium Bleed technique using a Kistler Miniature Quartz Transducer at the end of a 0.040 inch diameter passage 3/4 inches long. Acoustic properties of helium gas provided a system resonance of 12,500 Hz and a flat amplitude ratio to above 2,500 Hz. Progress in the development of the technique is found throughout the Princeton Aeronautical Engineering Reports of Appendix B. Reference (9) is presented as a starting point and Reference (10) as a special study in the dynamic response of small passage connected transducers. The assemblies discussed here are the most recent devices employing the technique.

(1) Aerojet-General Corporation Model HB3X-1

The AGC Model HB series represent successive stages of development in their efforts to obtain a transducer for use in the Gemini Stability Improvement Program.

The Model HB3X-1 of Figure 21 was, at the time of evaluation at Princeton, one of the most recent models in the series. It is shown in cross-section in Figure 22. A Summary Laboratory Evaluation is presented as Table V. The usual excellent linearity and hysteresis of the Kistler 601A

TABLE IV

Transducer Summary Laboratory Evaluation

Manufacturer: Kistler Instrument Corporation

Model: 616A Serial: 5163 Measurand: Dynamic Pressures

Pressure Range: 10-3000 psi Temperature Range: -450 to +500°F

Transduction Method: Electrostatic utilizing charge amplifier

Dimensions: Length 2.625 in. Width 0.900 in. Height 0.900 in. See Attached Dwg.

Weight 0.375 lbs.

Electrical Measurements: Resistance across Input ______ ohms

Resistance across Output ______ ohms

Resistance to Ground 10^{14} ohms

Excitation: Piezoelectric Other Electrical Data: Crystalline quartz sensing element

Coolant Conditions: Average Pressure 1000 lb in^{-2} gage Water Flow 0.126 lb sec^{-1}

Other Coolant Data: ______

STATIC PERFORMANCE

Without Coolant		With Coolant
9.87 volts @ 2000 psi	Full Scale Output	9.87 volts @ 2000 psi
0.96 p Cb/psi	Sensitivity	0.96 p Ch/psi
0.03 volt	Zero Output	0.14 volt
0.071 volt (ang)	Maximum Deviation in Output from Computed Straight Line	0.074 volt (ang)
	Drift Rate at Zero Pressure	0.27 psi/min

Coolant Temperature Rise per Unit Heat Flux: 1.09°F/Btu in^{-2}sec^{-1}

DYNAMIC PERFORMANCE

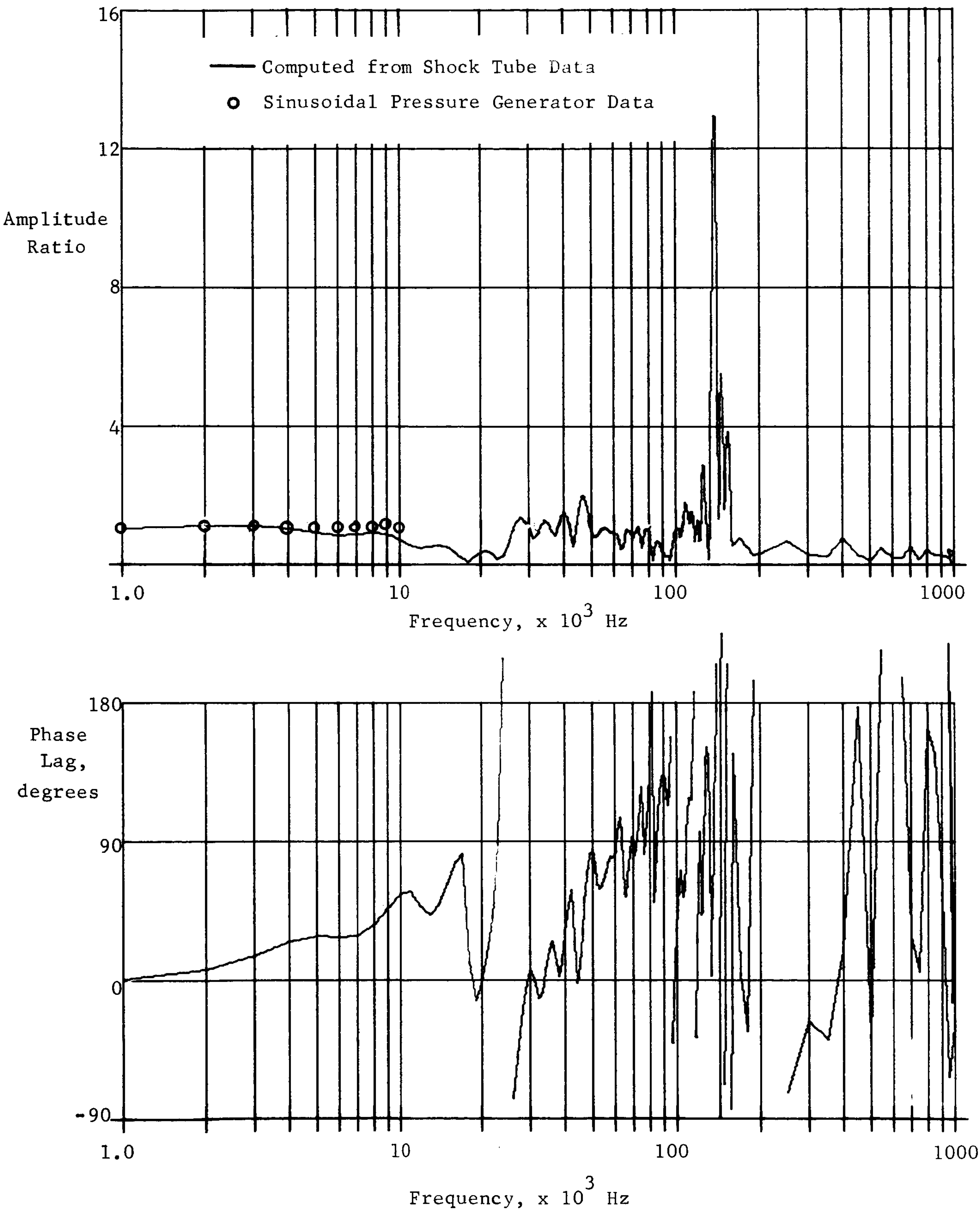
Resonant Frequency ______ Hertz. See Attached Response Curves

Amplitude Ratio, Flat to within ±10 percent up to 10,000 Hz 6,000

COMMENTS

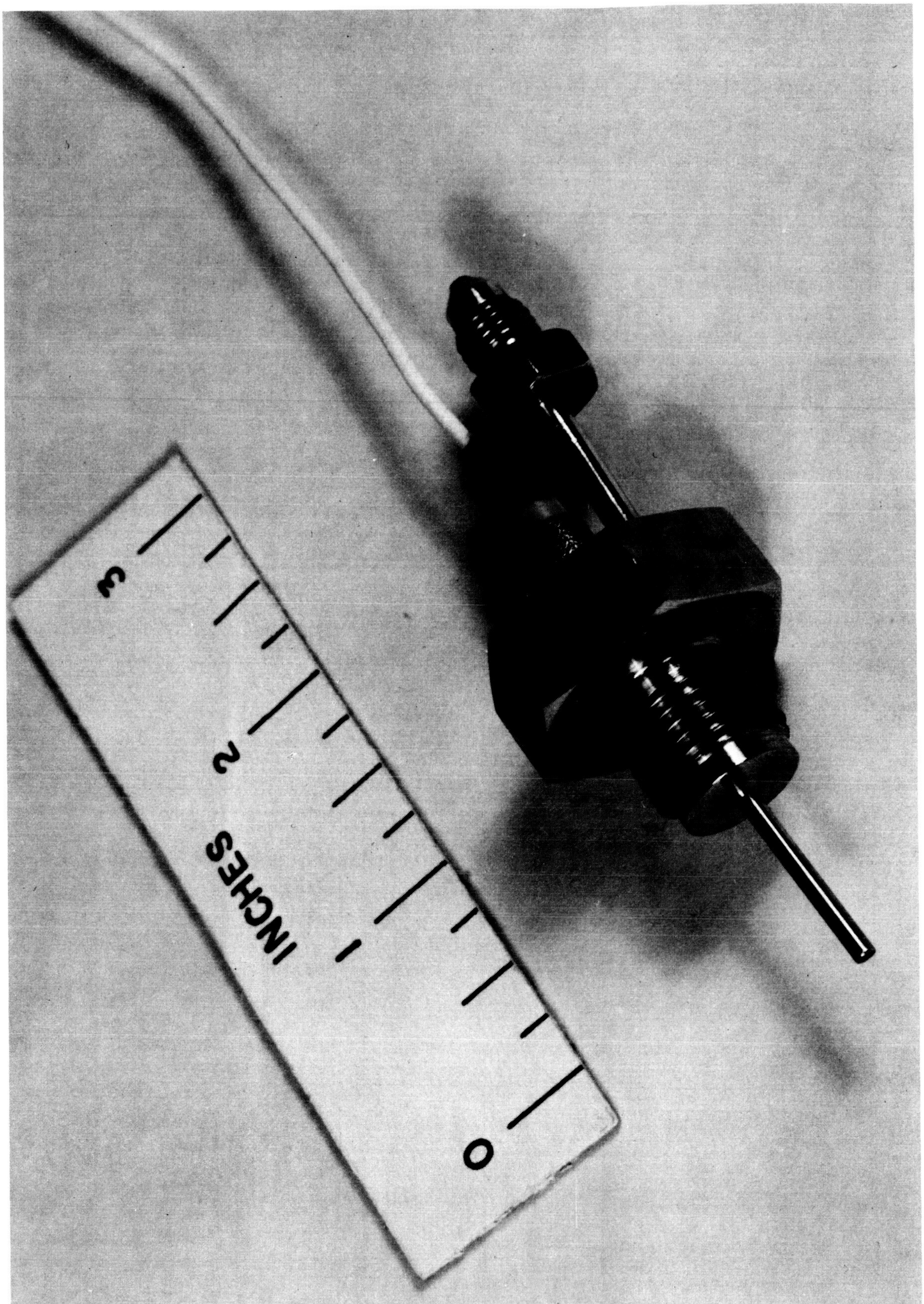
Kistler Model 504 charge amplifier used for this evaluation.

Initial and Date J.P.T.



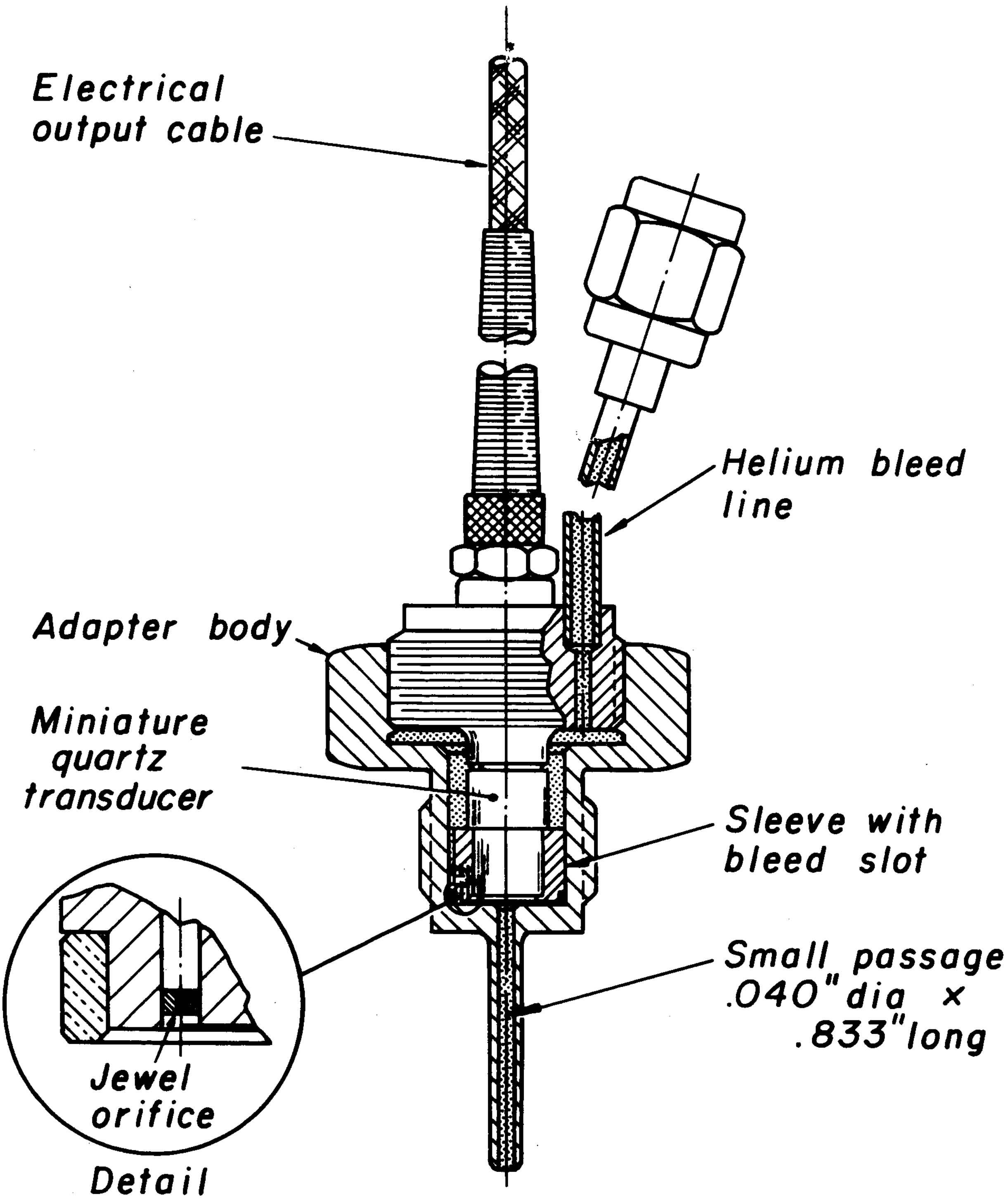
Dynamic Performance of Kistler Model 616A Serial No. 5163

FIGURE 20



Photograph of Aerojet-General Corporation Model HB3X-1
Small Passage Technique Adapter

FIGURE 21



Sectional Drawing of AGC Model HB3X-1
Small Passage Technique Adapter

FIGURE 22

JP24-JPR 4001-65

TABLE V

Transducer Summary Laboratory Evaluation

Manufacturer: Aerojet-General Corporation

Model: HB3X-1 Serial: 002 Measurand: Dynamic Pressure

Pressure Range: 10-3,000 psi Temperature Range: ______

Transduction Method: Electrostatic-charge amplifier, small passage technique

Dimensions: Length 3.25 in. Width 1.30 in. Height 1.30 in. See Attached Dwg.

Weight ______ lbs.

Electrical Measurements: Resistance across Input ______ ohms

Resistance across Output ______ ohms

Resistance to Ground $\sim 10^{14}$ ohms

Excitation: Piezoelectric Other Electrical Data: Kistler 601A transducer with crystalline quartz sensing element.

Coolant Conditions: Average Pressure ______ lb in^{-2} gage Water Flow ______ lb sec^{-1}

Other Coolant Data: Helium bleed

STATIC PERFORMANCE

Without Coolant		With Coolant
10.25 volts @ 2000 psi	Full Scale Output	
1.035 p Cb/psi	Sensitivity	
0.2 volts	Zero Output	
	Maximum Deviation in Output from Computed Straight Line	
	Drift Rate at Zero Pressure	

Coolant Temperature Rise per Unit Heat Flux: ______

DYNAMIC PERFORMANCE

Resonant Frequency 9500 Hertz. See Attached Response Curves

Amplitude Ratio, Flat to within ± 10 percent up to 10,000 Hz 2000

COMMENTS

Kistler charge amplifier Model 566 used for this evaluation, set at 10 mv/pCh.

Helium bleed pressure ≧ 2.08 maximum encountered pressure.

Initial and Date J.P.T.

transducers was present in the static pressure calibrations (2). The HB3X-1 exhibited a flat response ($\pm$ 10%) to 2000 Hz with a peak amplitude ratio of 3.9 occurring at 9500 Hz. Dynamic compensation with a matched electronic filter extended the flat response to 8000 Hz. Response curves, from Sinusoidal Pressure Generator data, are plotted in Figure 23. An explanation for the irregularity at about 5500 Hz was found in the study of passage connected transducers (9) where an assembly in the HB3X-1 configuration except for helium bleed passage configuration, showed no irregularities. This is demonstrated in the Panoramic Analyzer data of Figure 24. Modifications to the helium bleed sleeve and pressure seal were made and the final model (5) in the development program, the Model HB3X-2, evolved.

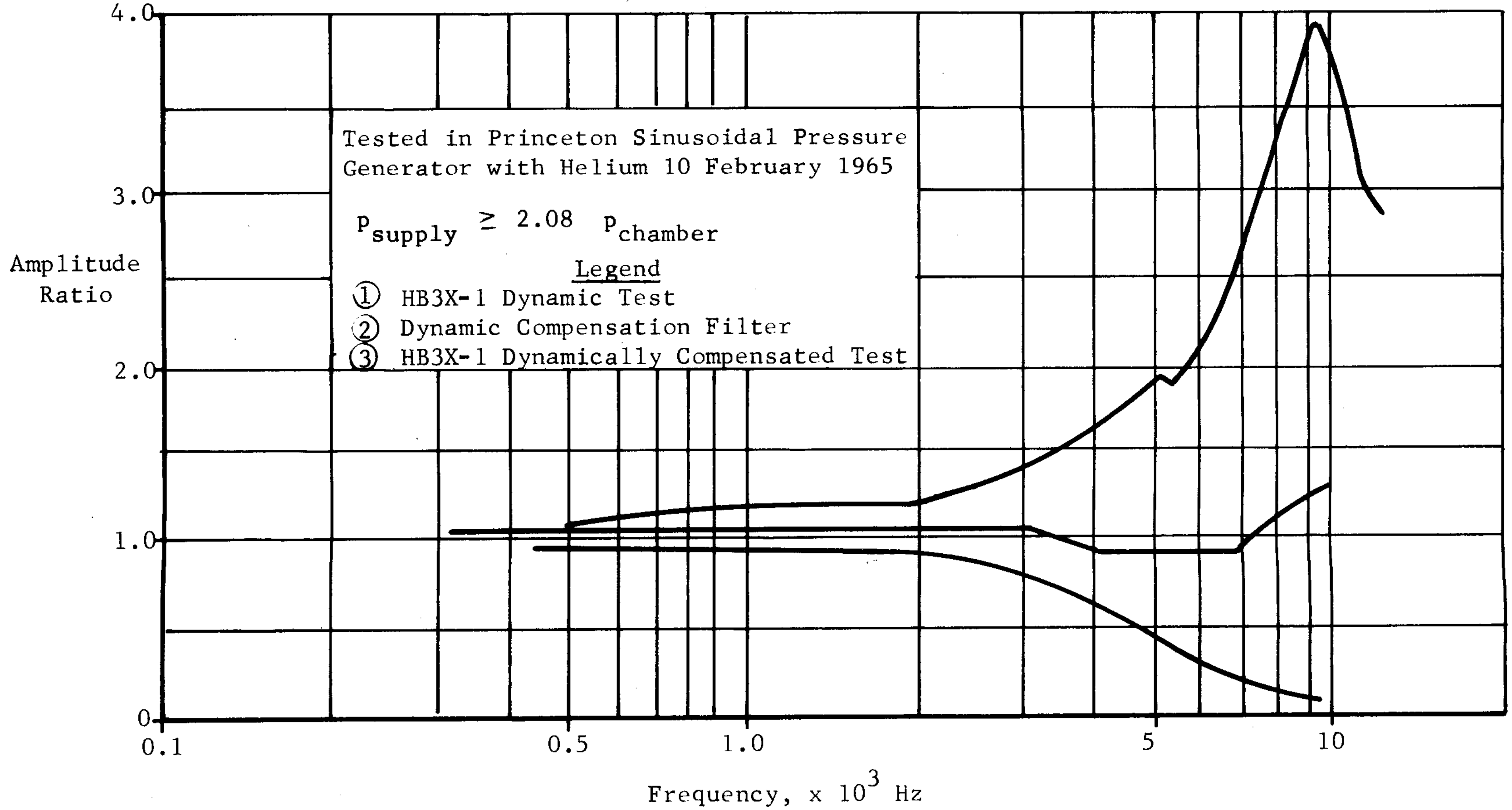
(2) Aerojet-General Corporation Model HB4X-1

Although development of the AGC HB series of transducer assemblies had satisfied the GEMSIP Program up to and including the Model HB3X-2, Aerojet-General carried development further in the Model HB4X-1. A Summary Laboratory Evaluation is included as Table VI.

The significant difference between the HB4X-1 and the HB3X-1 just discussed was in the small passage which varied in diameter by several thousandths of an inch in four steps along its length. Amplitude ratio vs frequency is seen in Figure 25 to peak at 5.1 at a frequency of 7500 Hz with a flat response ($\pm$ 10%) to 2000 Hz. The curve, generated from SPG data, was the smoothest curve of all small passage technique transducers so generated at the close of the research.

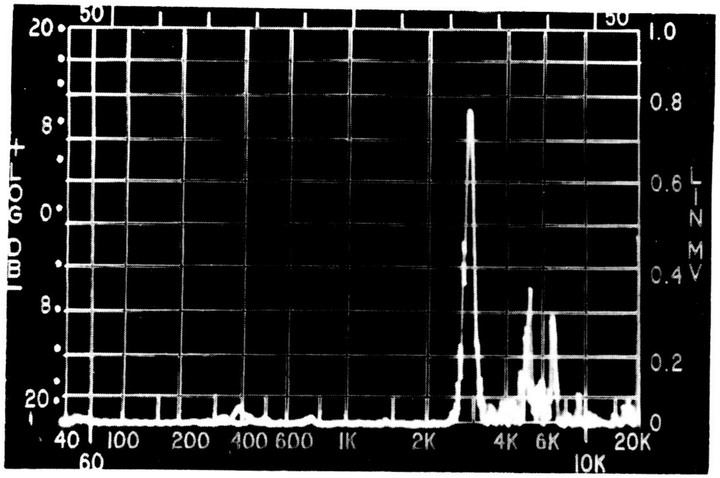
(3) Kistler Models 614 and 615

The Kistler Models 614 and 615, in the early development stage at the close of the research at Princeton, are shown in Figure 26. The Model 615

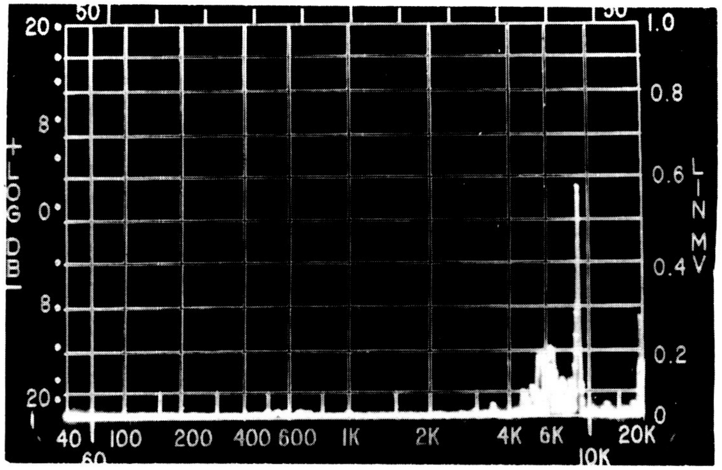


Amplitude Ratio vs Frequency from Princeton Sinusoidal Pressure Generator
for AGC Model HB3X-1 Serial No. 002

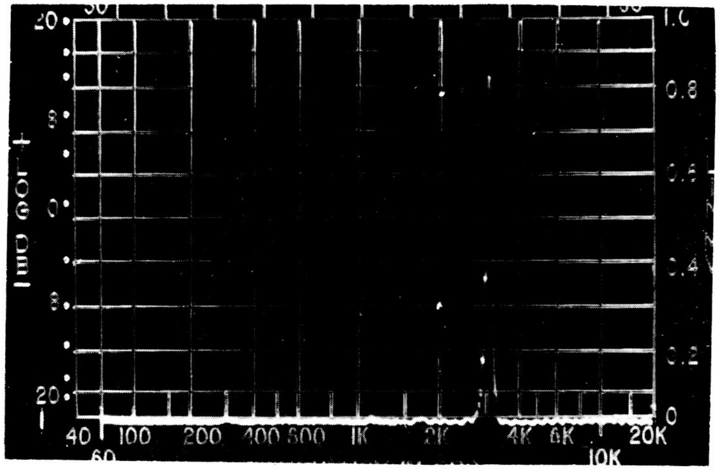
FIGURE 23



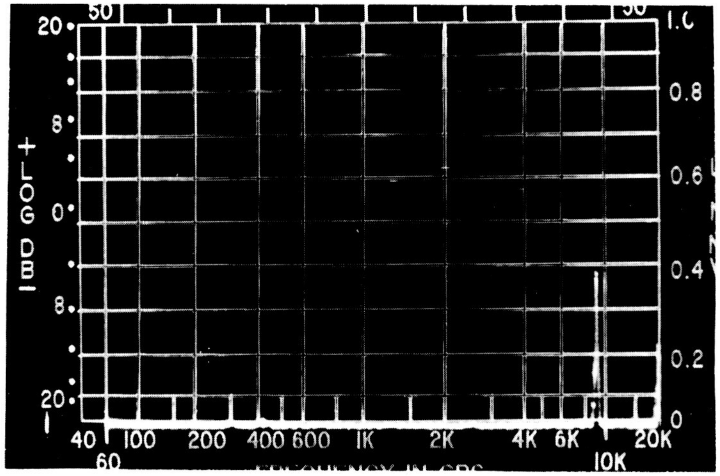
A. HB3X-1 At 3000 Hz



B. HB3X-1 At 9500 Hz



C. GL 030 At 3000 Hz



D. GL 030 At 9500 Hz

Amplitude vs Frequency from Panoramic Analyzer for AGC
Model HB3X-1 and Guggenheim Laboratories Model GL 030
at Excitation Frequencies of 3000 and 9500 Hertz.

FIGURE 24

TABLE VI

TRANSIENT PRESSURE TRANSDUCER SUMMARY LABORATORY EVALUATION

Manufacturer: Aerojet-General Corporation

Model: HB4X-1 Serial: 001 Measurand: Dynamic Pressures

Pressure Range: 10-3000 psi Temperature Range: ______

Transduction Method: Electrostatic, Charge Amplifier, Small Passage Technique

Dimensions: Length 3.25 in. Width 1.30 in. Height 1.30 in. See Attached Dwg.

Weight ______ lbs.

Electrical Measurements: Resistance across Input ______ ohms

Resistance across Output ______ ohms

Resistance to Ground 10^{14} ohms

Excitation: Piezoelectric Other Electrical Data: Kistler 601A Transducer with crystalline quartz sensing element

Coolant Conditions: Average Pressure ______ lb in^{-2} gage Water Flow ______ lb sec^{-1}

Other Coolant Data: Helium Bleed

STATIC PERFORMANCE

Without Coolant		With Coolant
10.93 volts @ 2000 psi	Full Scale Output	
1.097 p Ch/psi	Sensitivity	
0.073 volt	Zero Output	
0.026 volt (ang.)	Maximum Deviation in Output from Computed Straight Line	
	Drift Rate at Zero Pressure	

Coolant Temperature Rise per Unit Heat Flux: ______

DYNAMIC PERFORMANCE

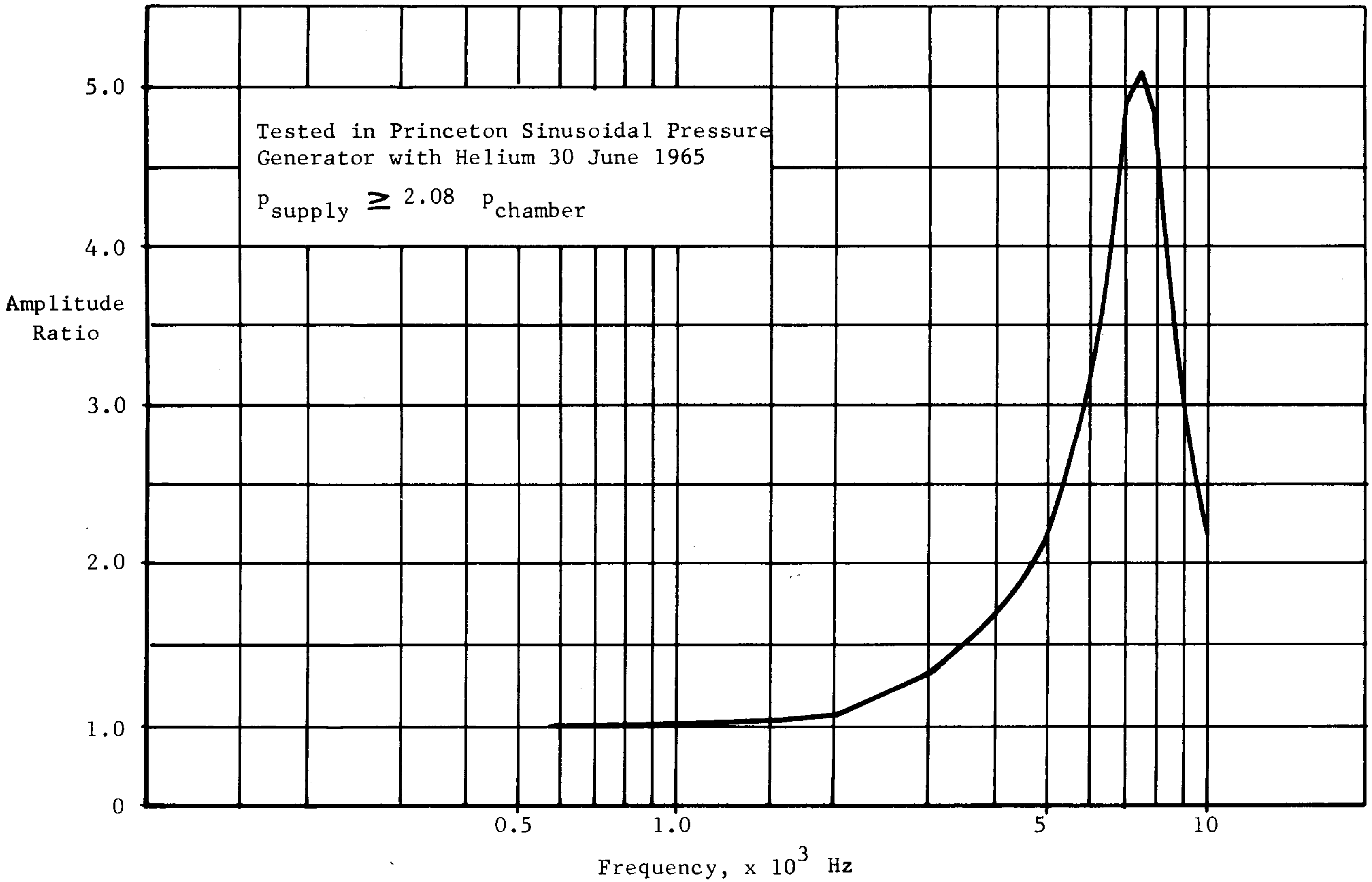
Resonant Frequency 7500 Hertz. See Attached Response Curves

Amplitude Ratio, Flat to within ± 10 percent up to 10,000 Hertz 2000

COMMENTS

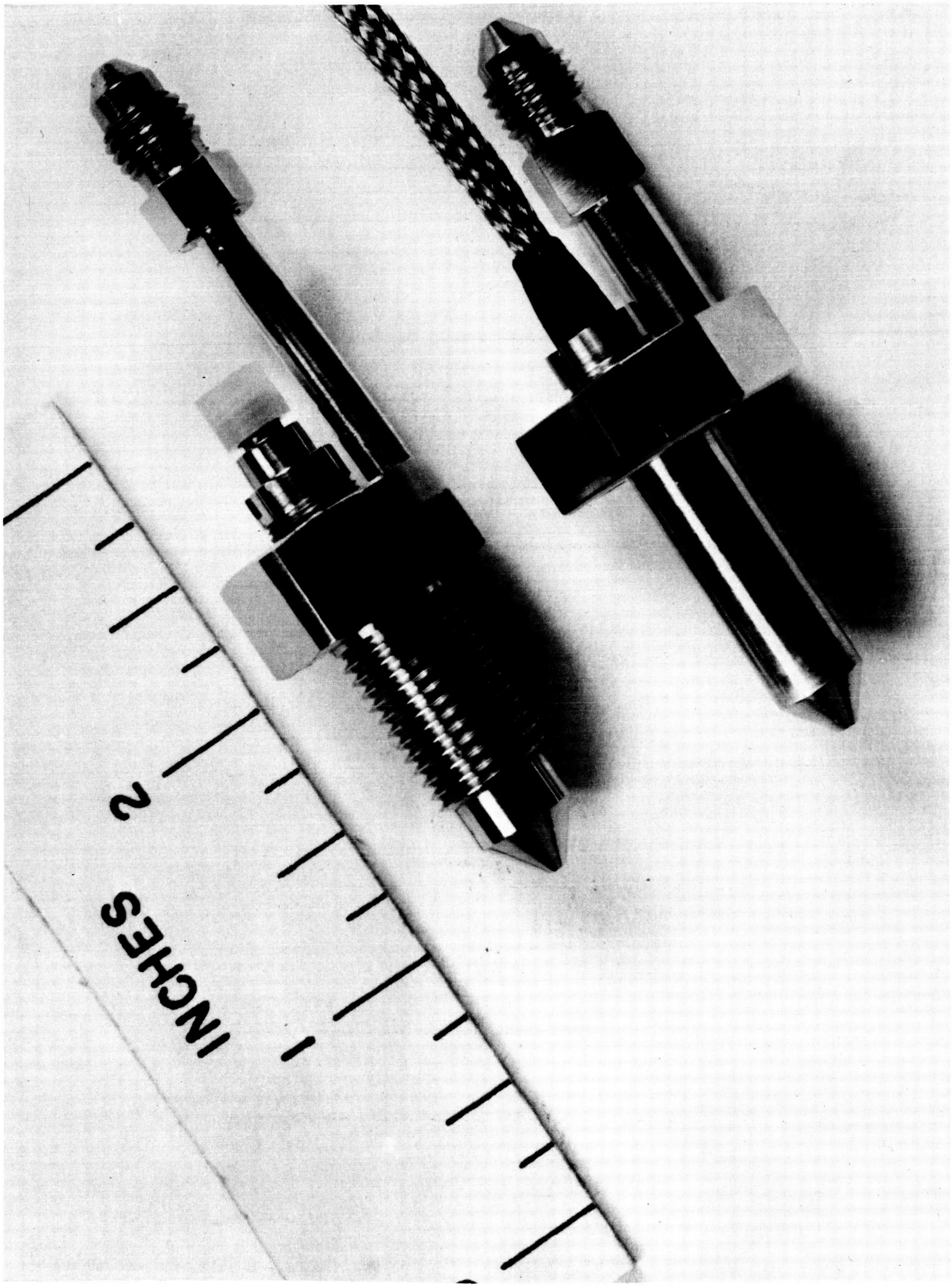
Kistler Model 566 charge amplifier used for this evaluation. Helium bleed pressure 2.08 maximum encountered pressure.

Initial and Date J.P.T. 7/14/65



Amplitude Ratio vs Frequency from Princeton Sinusoidal Pressure Generator for AGC Model HB4X-1 Serial No. 001

FIGURE 25



Photograph of Kistler Models 614 (below) and 615 (above)
Small Passage Technique Adapters

FIGURE 26

has a 7/16-24 mounting thread and flared seat seal. The Model 614 is designed for flange mounting. Soft copper flare seals may be used with each.

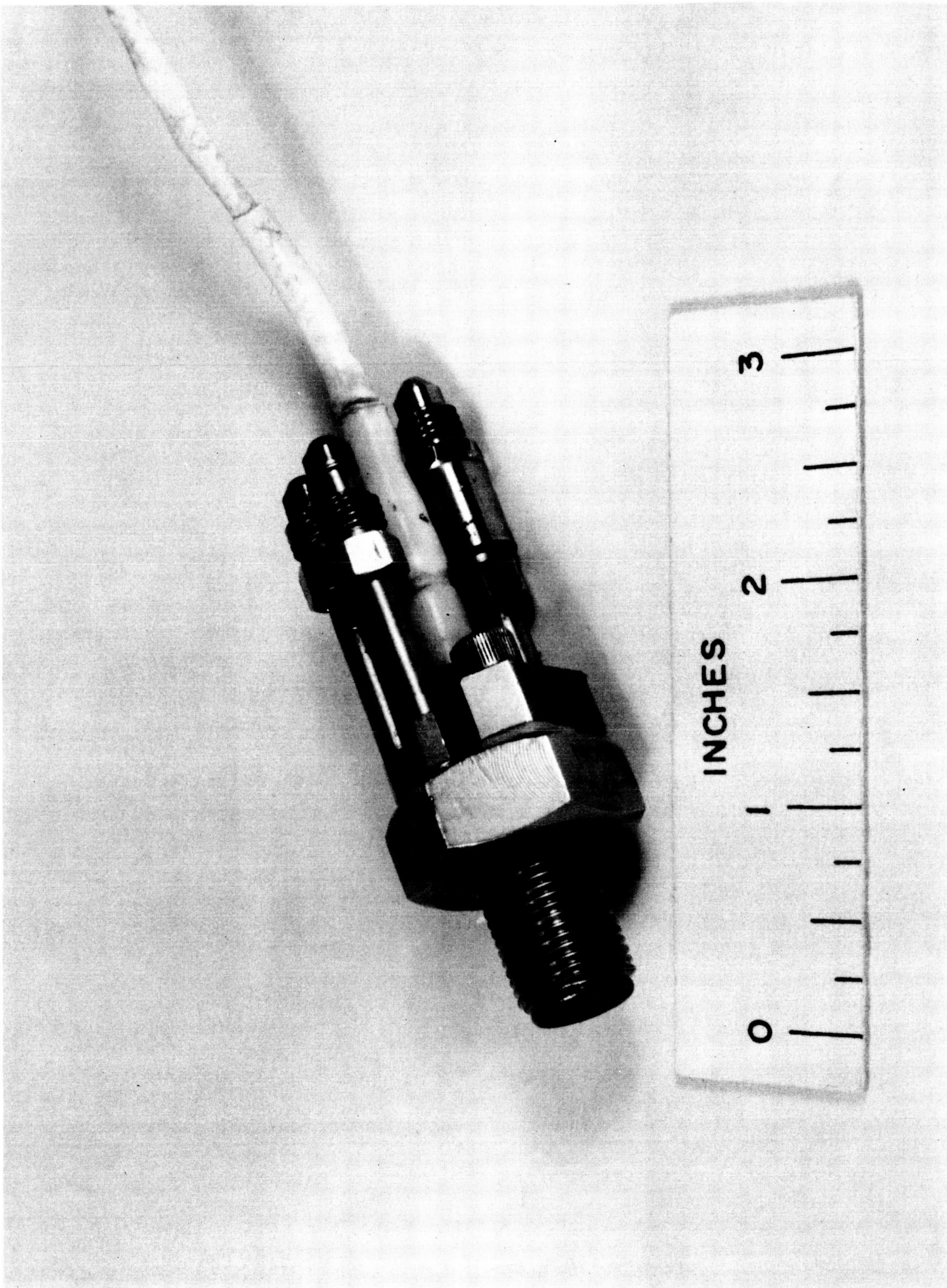
(4) Kistler Model 614/644

The Kistler Model 614/644 shown in Figure 27 encloses the Model 614 helium bleed adapter in a water-cooled adapter to give a total passage length of 3/4 inch. This combination was received too late for evaluation but may have applicability when rocket tests are of some duration depending on its heat transfer capability.

(5) Guggenheim Laboratories Model GL029

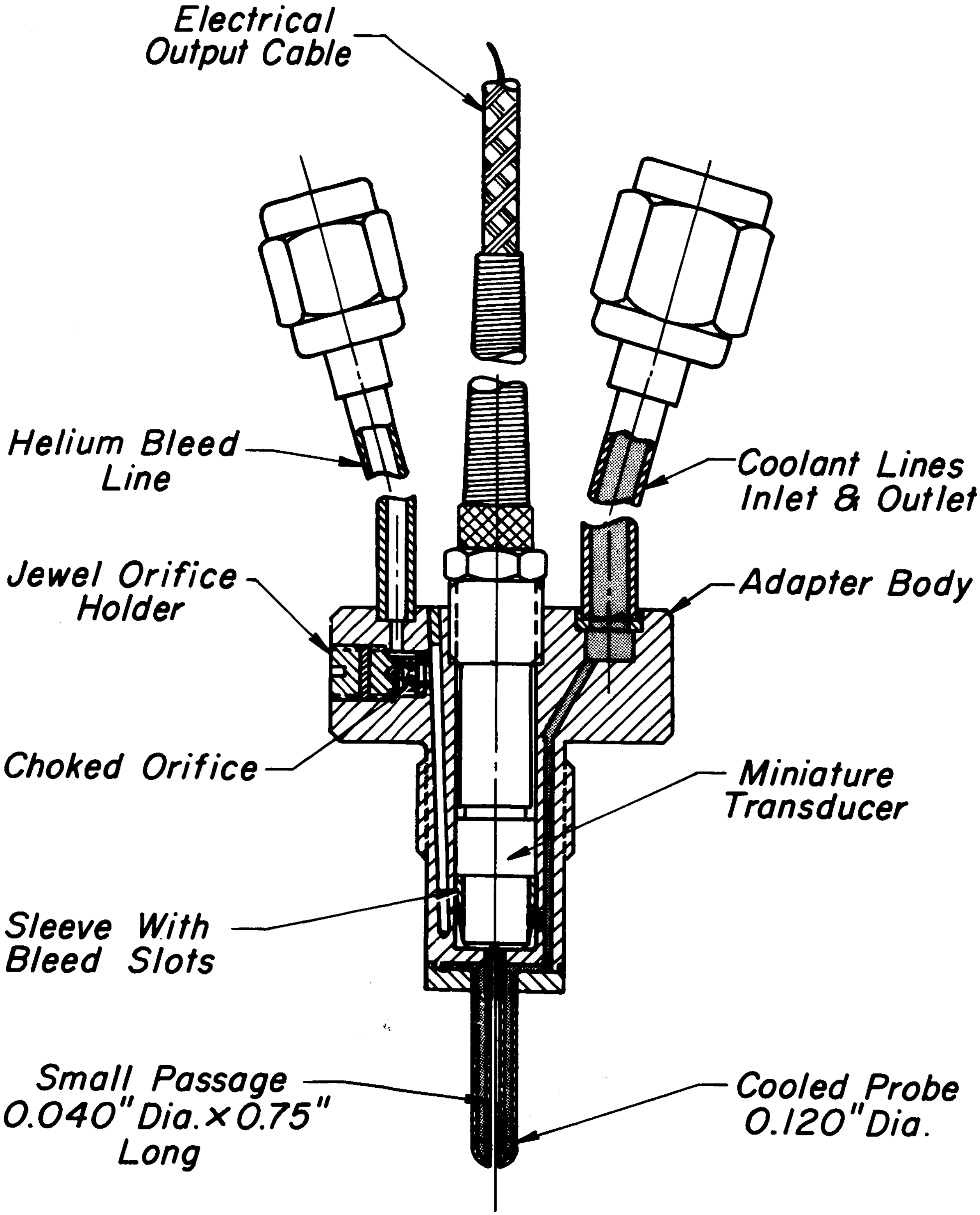
The progress made with the small passage helium bleed technique adapters warranted a cooled probe adapter which would withstand the heat flux in high performance rocket motors, especially uncooled thrust chambers used in research and development. Experience with small cooled probes, used to sample hot ionized gases supported the design of the GL029 adapter shown in Figure 28. Fabrication was undertaken by NASA Marshall Space Flight Center.

It was expected that thermal drift and probe erosion would be eliminated or at least reduced sufficiently to preserve steady state data. Unfortunately, the outer coolant shell collapsed either from loading on the gasket area, due to thermal growth, or under external pressure. The failure was not noticed until coolant flow dropped and the unit was removed from hardward used to adapt small transducer assemblies to the large cavities in the laboratory test equipment. Hot testing was eliminated because of the coolant flow restriction and the unit was sectioned, as shown in the FRONTISPIECE, to determine the cause of failure and for



Photograph of Kistler Model 614/644 Passage Connected Transducer

FIGURE 27



Sectional Drawing of Guggenheim Laboratories Model GL029
Small Passage Technique Adapter

FIGURE 28

JPR 2568

redesign information. A partial Summary Laboratory Evaluation is provided as Table VII. Amplitude ratio vs frequency without coolant flow from the Princeton Sinusoidal Pressure Generator is found in Figure 29, but should be considered only preliminary.

B. Target Characteristics for Advanced Transducers

The following target characteristics for a miniature, cooled, flush diaphragm transducer and short passage connected transducers, including gas bleed technique adapters, are presented as a means of directing attention toward needed developments for both transient and steady state pressure measurements. Transducers with these characteristics would find wide usage not only in liquid propellant rocket testing, but in other aerospace propulsion system research and development and in many other research and development efforts. There are a considerable numberof other applications requiring specialized pressure transducers in the near and farther future; e.g., higher level measurements in steady flow systems including under non-steady conditions, control system sensors, pulse rockets, nuclear power and propulsion systems, etc. Target characteristics are not included for any of these applications because it was not possible to give adequate attention to either the detailed requirements or the pertinent measurement methodology.

1. Miniature, Cooled, Flush Diaphragm Transducers

a. General

The target characteristics presented here represent a badly needed advanced capability for transient pressure measurements under difficult conditions of very high pressure and temperature and restricted accessibility that exist in advanced rocket systems and in many other areas of research and development.

TABLE VII

Transducer Summary Laboratory Evaluation

Manufacturer: Guggenheim Laboratories (Fabricated by MSFC)

Model: GL029 Serial: Prototype Measurand: Dynamic Pressure

Pressure Range: 10-3000 psi Temperature Range: ______

Transduction Method: Electrostatic-charge amplifier, small passage technique

Dimensions: Length 3.25 in. Width 1.30 in. Height 1.30 in. See Attached Dwg.

Weight ______ lbs.

Electrical Measurements: Resistance across Input ______ ohms

Resistance across Output ______ ohms

Resistance to Ground $\simeq 10^{14}$ ohms

Excitation: Piezoelectric Other Electrical Data: Kistler 601A transducer with crystalline quartz sensing element

Coolant Conditions: Average Pressure 2000 lb in^{-2} gage Water Flow ______ lb sec^{-1}

Other Coolant Data: Helium bleed

STATIC PERFORMANCE

Without Coolant		With Coolant
10.96 volts @ 2000 psi	Full Scale Output	
1.089 p Cb/psi	Sensitivity	
0.080 volts	Zero Output	
	Maximum Deviation in Output from Computed Straight Line	
	Drift Rate at Zero Pressure	

Coolant Temperature Rise per Unit Heat Flux: ______

DYNAMIC PERFORMANCE

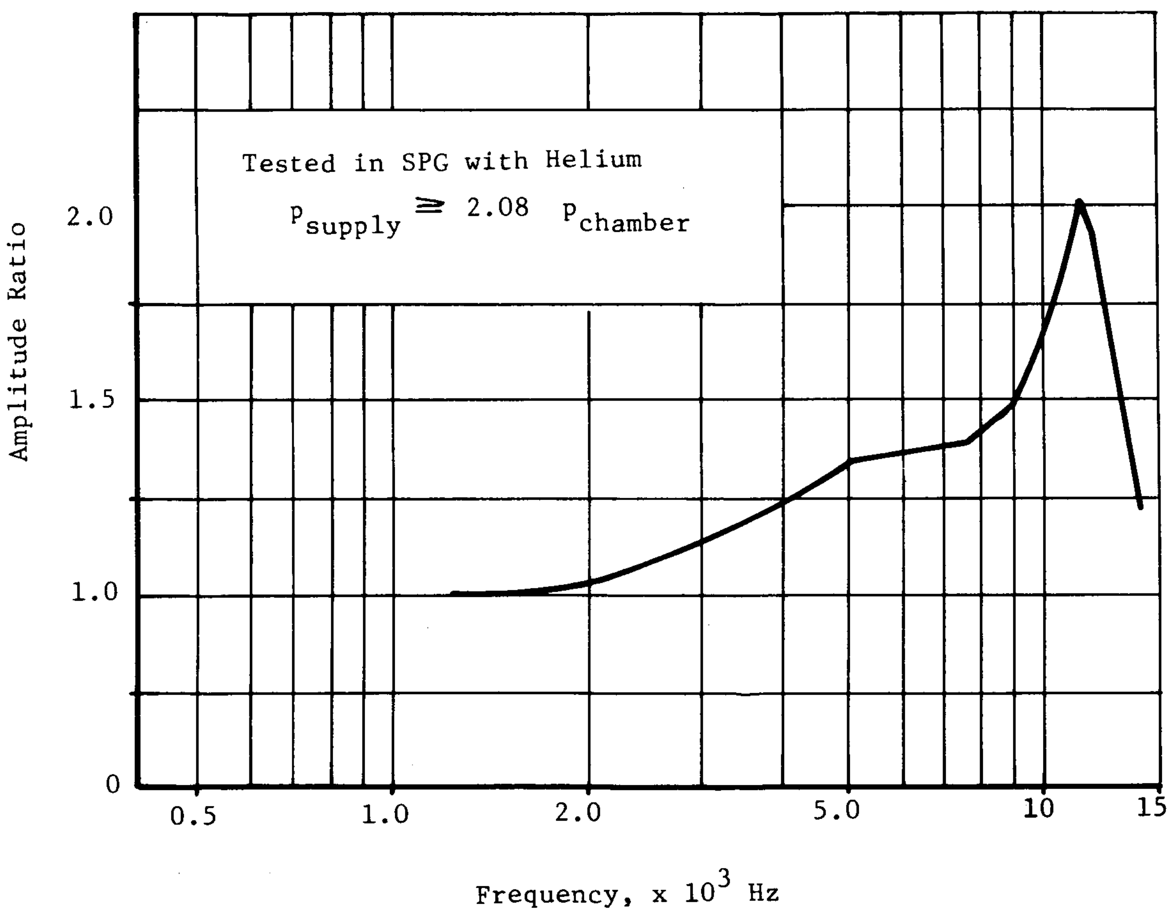
Resonant Frequency 11500 Hertz. See Attached Response Curves

Amplitude Ratio, Flat to within ± 10 percent up to 10, 000 Hz 2500

COMMENTS

Kistler Model 504 charge amplifier used for this evaluation. Helium bleed pressure $\geqq$ 2.08 maximum encountered pressure.

Initial and Date J.P.T.



Amplitude Ratio vs Frequency
from Princeton Sinusoidal Pressure Generator
for Guggenheim Laboratories Model GL029

FIGURE 29

(1) Application

The measurement of transient pressure in liquid propellant rocket combustion chambers is recognized as one of the more difficult problems in advanced metrology because accurate dynamic measurement of rapidly varying (including shock) pressures in very high temperature gases must be made under extreme environmental conditions in combustion with severe mounting restrictions and high reliability requirements. The need for these measurements extends throughout research and development testing including flight firings of rocket propelled launch vehicles and spacecraft.

Transient pressures occur in liquid propellant rocket thrust chambers during start-up and shut-down and during combustion instability. Chamber pressures range from around 100 to over 3000 lb. in^{-2}. Pressure rise rates can exceed 1×10^6 lb. in^{-2}sec^{-1} under normal operation and occur at much higher rates in combustion shock fronts. Oscillation sometimes involve peak-to-peak pressures of 200% of the average chamber pressure with higher "spiking." Oscillatory frequencies over 10,000 Hz are encountered in unstable combustion and the definition of wave forms requires an essentially flat response to 100,000 Hz.

(2) Environment

The environment inside the rocket combustion chamber is not severe. Combustion temperatures up to 7000R and pressure waves producing vibrational accelerations to 1000g and above characterize the basic environment. Ambient temperatures from cryogenic propellants are often near absolute zero and are raised thousands of degrees in milliseconds during start-up.

The external environment is conditioned by flaring exhaust gases and corrosive and dirt lade air on the test stand and in flight by pressures extending down to extremely low vacuum and temperatures near absolute zero, except in enclosed areas or areas subject to exhaust gas impingement.

b. Transmission

(1) Fundamental Methods

A considerable number of methods based on quite different fundamental processes have been used for generating electrical signals proportional to pressure. Those listed below are selected as the most promising for the present application:

(a) Bonded Wire Resistive Strain Gauge Bridge

Wires of various compositions are bonded with resins or other cementing agents to tubes or other elements that are strained by pressure forces. The wires are configured to form a four active arm wheatstone bridge so the mechanical and any thermal strain yield an electrical output linear with pressure that is proportional to the excitation voltage.

(b) Variable Capacitance

Pressure forces are used to change the dimensions of a gap filled by a dielectric which gives a change in capacity that can be combined with electronic circuitry to provide a linear output with pressure that is essentially drift free.

(c) Piezoelectric Crystals

The application of force to certain planes of an elastic crystal deforms the structure with a resultant flow of electrons that gives a charge across the crystal directly proportional to the force. Quartz crystals properly used in miniature transducers with electrostatic charge amplifiers can provide excellent long time constant static as well as transient pressure measurements.

(d) Semiconductor Strain Gage Bridge

Doped silicon crystals are being used as resistance elements applied to strained columns, diaphragms, etc., in micro-sized bridge arrangements with thermal and mechanical strain compensation and comparatively high gage factors.

(2) Electrical Output

The transduction method selected must be used in the transducer so that the electrical output under operating conditions is free from design dependent charges that result in shifts, drifts and sensitivity charges including non-linearity, hysteresis, etc. The mounting and cooling design features should not introduce variations in the electrical output.

Zero electrical output should be provided at zero pressure.

The following outputs are typical of the several transduction methods listed above:

(a) Bonded Wire Resistive Strain Gauge	0.001 to 0.002 mv/v/psi
(b) Variable Capacitance	0.002 $\mu\mu$f/psi
(c) Piezoelectrice (Quartz)	0.35 to 5.0 pCb/psi
(d) Semi-Conductor Strain Gage	0.03 to 0.3 mv/v/psi

Properly designed auxiliary equipment that is matched to a specific transducer must be used to produce easily measured voltages without loss of precision or accuracy from spurious signals, noise, etc.

c. Steady State Performance

(1) Zero Drift

Drift from thermal and other effects that are present while the transducer is being brought into operation should be minimized. Mechanical, thermal and electrical design techniques must be exploited fully to reduce long term shifts in zero pressure output although some compromise in steady state performance may be necessary to attain thermal capabilities, dynamic response and other characteristics. Long term zero drift should not exceed 0.1% full scale.

(2) Sensitivity Change

Changes in sensitivity must be prevented or compensated to a high degree to minimize the effect on both steady state and transient output. A sensitivity change over the full linear range that does not exceed $\pm$ 0.05% from all causes is extremely desirable.

(3) Linearity

Deviation from a computed best fit straight line to a static pressure calibration should not exceed 0.25% over the full scale range of the transducer.

(4) Hysteresis

The maximum hysteresis exhibited over the full scale range should not exceed 0.05% of full scale output.

d. Dynamic Performance

(1) Response

The dynamic performance should yield a flat ($\pm$10%) response to 100.000 Hz. This will require a primary resonant frequency of over 350,000 Hz to transducers with typically low damping.

(2) Vibration Sensitivity

The transducer should be insensitive over the entire range of mechanical vibration. Acceleration sensitivity of less than 0.01% FS per g is highly desirable.

e. Thermal Design

The design of transducer must be aimed at the incorporation of cooling provisions with little or no compromise of other characteristics. The diaphragm and/or other surfaces exposed to the maximum temperatures must be cooled or otherwise protected. The sensing elements of the transducer need also to be shielded from cryogenic propellants and other thermal sinks and sources so the range of temperature compensation is kept reasonable. Mechanical strains that are produced thermally must be recognized in the design of the transducer. Coolant pressures, which should be well above the maximum pressure measurement capability of the transducer, must not produce zero or sensitivity changes and coolant flows should not introduce appreciable noise.

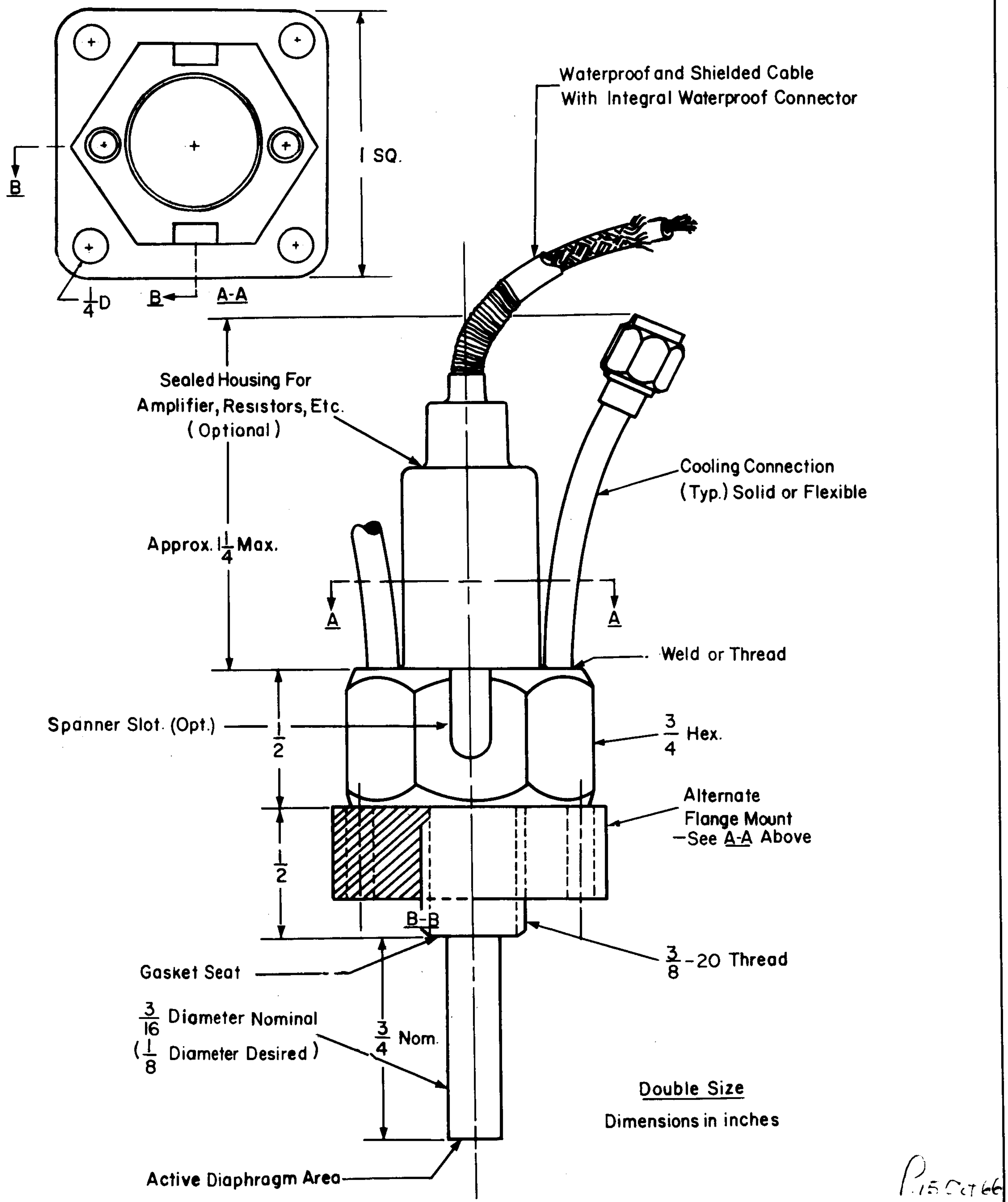
Transducers for rocket combustion pressure measurements must withstand stabilized thermal conditions produced by fully developed high frequency transverse instability where the adjacent chamber wall is experiencing heat fluxes around 60 BTU in^{-2} sec^{-1}. Localized heat flux in shock and strong pressure waves may exceed this value and in addition sweep away any protective boundary layers. Protective coverings, including ceramic, ablative and other materials, may often be applied to exposed surfaces.

The transducer design should be configured so that burnout or other failure of the diaphragm or other areas exposed to combustion pressure does not allow the escape of combustion gases.

f. Mechanical Design

(1) General Configuration

The general configuration of the transducer should be similar to that shown in Figure 30. Target dimension should be carefully noted. The active diaphragm area at the end of the 3/4 inch long



Target Outline Drawing of a Miniature, Cooled, Flush Diaphragm Transient Pressure Transducer

FIGURE 30

cylindrical section is intended for flush location with the wall of the combustion chamber or containment vessel in which the pressure measurement is to be made. Because of space limitations between cooling passages, as in a regeneratively cooled liquid propellant rocket thrust chamber, as well as the desire for a localized pressure measurement, the diameter of the transducer diaphragm and shank should be no greater than 3/16 inch with smaller diameters to 1/8 inch highly desired. The transducer body and other external parts should also be kept small because of space limitations posed by mounting restrictions posed by adjacent hardware, components, etc. The transducer should be designed for either thread or flange mounting with adequate attention being given to sealing against combustion gas leakage under extremely severe vibrations and other high loads.

(2) Material

The entire transducer, insofar as possible, must be fabricated from highly corrosion resistant materials. Other materials must be protected or sealed from moisture and highly corrosive hot gases. The diaphragm material must be especially corrosion proof and of high thermal conductivity and hot strength. Materials must be compatible and fabrication methods carefully selected.

(3) Mounting

The mounting configuration should recognize both the requirements and limitations of the transducer and its mounting boss. Stresses generated in attaining the pressure seal and other such effects, such as thermal expansion of the boss should have a minimal effect on the output of the transducer.

(4) Coolant Provisions

The coolant provisions should be carefully arranged to be adequately strong to withstand pressure and mechanical loads and remain leakproof. The coolant lines, preferably flexible, should terminate in female stainless steel flare fittings. Threaded connections should be safety-wired or locked.

(5) Electrical Connections

The electrical connections should be waterproof and comprise a shielded and supported cable with a smooth, integral cover with a waterproof connector and a shrinkable sleeve. The cable should be supported so that it is not strained and the threaded connections should be safety-wired or locked.

g. Reliability

EVERY EFFORT MUST BE DIRECTED TO ATTAIN THE HIGHEST RELIABILITY THAT PRESENT TECHNOLOGY CAN PROVIDE.

Each transducer must be tested in the laboratory against all specifications although operational tests may previously have established the acceptability and overall performance of the prototype design.

h. Miscellaneous

(1) Calibrations

Calibration data should be provided with each transducer in a form convenient for the user.

(2) Operating Information

Full operating instructions, that do not assume complete familiarity with handling and use of the type should be provided with each transducer.

2. Short Passage Connected Transducers, including Gas Bleed Technique Adapters

a. Fundamental Considerations

The transient pressure measurement capability of passage connected transducers depends primarily on the passage length and the speed of sound in the gas filling the passage. Other geometric factors have some effect. For short passages and carefully controlled geometry the resonant frequency can provide useful response* for the identification of combustion instability modes in liquid propellant rocket thrust chambers as is shown in Figure 31. The curves shown assume that the combustion gases are at combustion temperature in the full length of the passage. Helium at 60°F is seen to lie close to the combustion gas curves except for oxygen/hydrogen and thus is the basis for the use of the Princeton Sinusoidal Pressure Generator to evaluate the response of passage connected transducer systems. The uniform temperature of helium bleed gas and its predictable high response for very small passages with low heat flux is the basis for the Princeton Small Passage Helium Bleed Technique. The performance possible with this technique is shown for several gaps on Figure 32. The resonant frequency is somewhat reduced by the bleed flow in practical configurations.

b. Practical Applications

(1) Tubing Connected Transducers

If the geometry is carefully configured transducers may be connected by a length of tubing or other passage and yet provide a certain transient response (see Figure 31). However, the passage must be kept simple with a minimum of discontinuities and recesses. It has been shown that liquid filled lines do not provide an enhanced response and that installations representing a proper locations for the pressure

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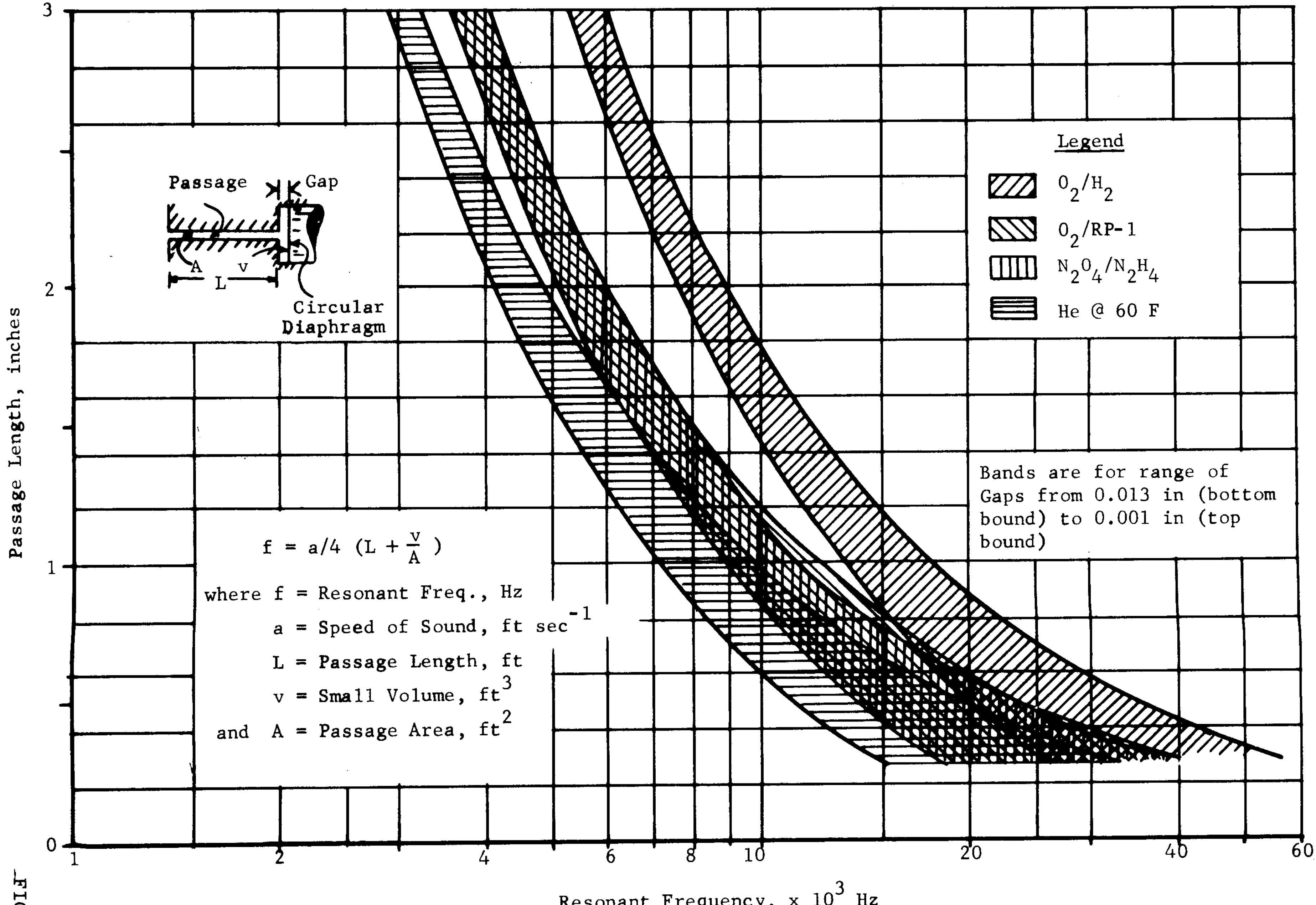
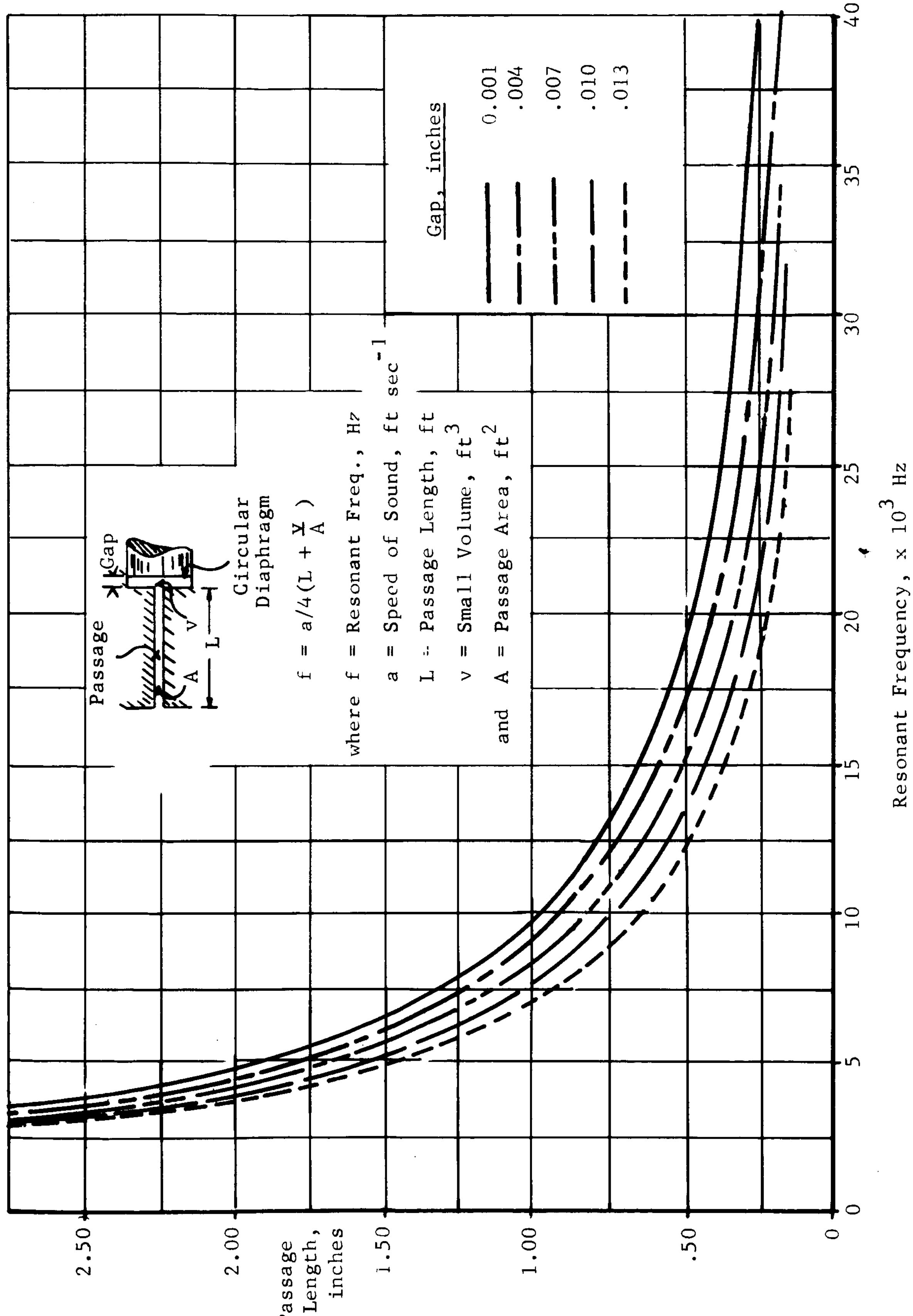
(*) Flat (± 10% of true amplitude) to 1/3 of the resonant frequency (depending somewhat on damping) or higher (to above 2/3 of resonant frequency with filtering).



Passage Length vs Resonant Frequency of Several Liquid Propellant Combustion Gases and Helium

FIGURE 31



Passage Length vs Resonant Frequency with Helium for Various Gaps

FIGURE 32

tap and a passage length that is a compromise between transient response and heating of the transducer and line can be serviceable if the transducer is carefully selected.

(2) Princeton Small Passage Gas Bleed Technique

The geometry for the Princeton Small Passage Gas Bleed Technique must be very carefully configures especially the bleed orifice and the manner of introducing the gas into the very small volume adjacent to the transducer diaphragm. Further research is required in this area of concern. Besides helium, hydrogen could be used to advantage as a bleed gas. Practical configurations used so far are shown and discussed in Section II above.

III. EVALUATION METHODS FOR TRANSIENT PRESSURE TRANSDUCERS

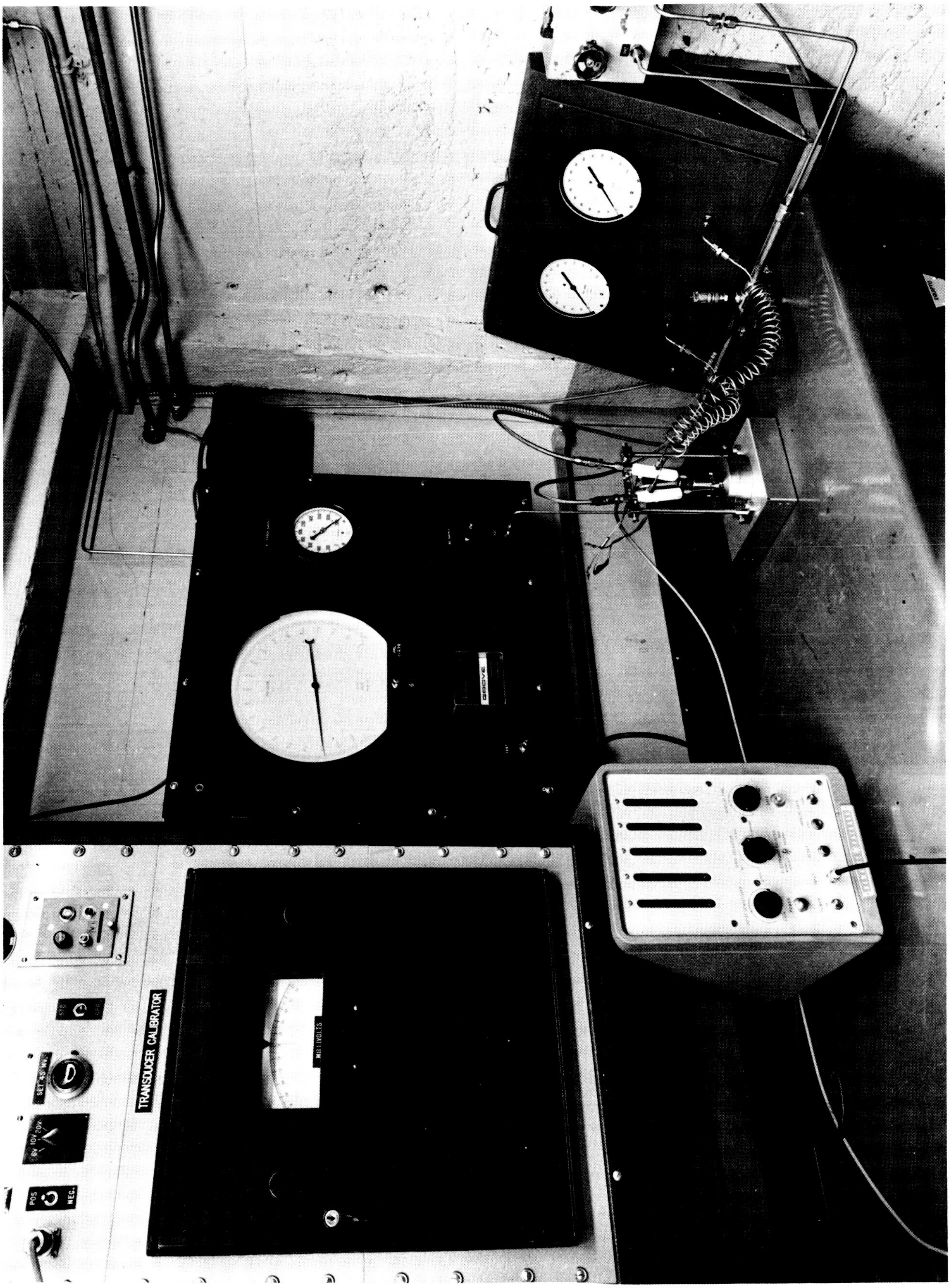
A. Laboratory Evaluations

A laboratory evaluation, following the procedure of Appendix E, will not only reduce time lost due to transducer weakness or damage, but may possibly save a rocket thrust chamber or other costly hardware should gasket leakage, transducer coolant system failure, mechanical or other failures occur. A visual inspection and/or electrical check may disclose a weakness or fault before static or dynamic calibrations are begun. The procedure of Appendix E was under continuous revision throughout the research at Princeton and sections of the procedure, which were necessary only for the research, may be eliminated for transducer evaluation where working an instrument beyond manufacturer's specifications or transducer development is not of interest.

1. Static Testing

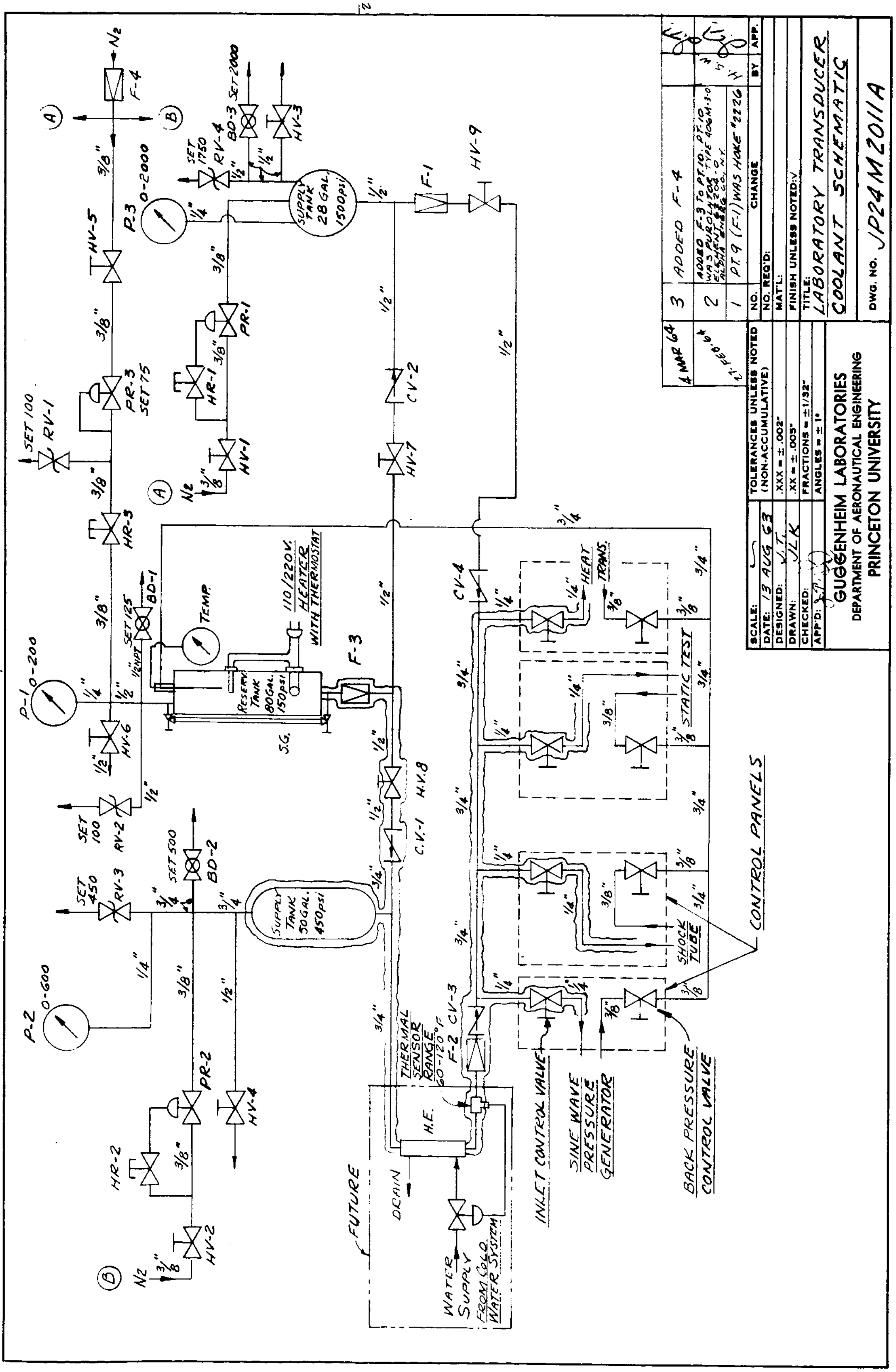
The gas pressurizing system shown in Figure 33 was designed chiefly to eliminate human error in accurately determining transducer output linearity and hysteresis with applied pressure without going to the expense of an elaborate automated system. It also provided a means of leak testing transducers, gaskets and seals and associated hardware. In conjunction with a transducer coolant system, coolant control panel and proper instrumentation, this station in the laboratory transducer evaluation procedure provided a means of transducer coolant pressure testing and a place to study effects of pressure and temperature transients on transducer sensitivity and zero stability.

The test gauge, used to monitor pressure applied to transducers



Photograph of Transducer Static Pressure Calibrating System

FIGURE 33



Schematic Drawing of Transducer Coolant System

FIGURE 34

was a Heise bourdon tube type with a 0-2000 lb. in^{-2} range, 1 lb. in^{-2} graduations, zero lash and no detectable hysteresis or nonlinear characteristics on a 5lb. increment dead weight test. A Grove pushbutton regulator with an adjustable touch sensitivity was selected for delicate approach to pressure calibration points in both upscale and downscale directions.

a. Transducer Output

Transducer output was monitored continuously, during transducer coolant flow and pressure testing, drift testing and static pressure calibrations on a ± 60 millivolt indicating potentiometer with a readout sensitivity of 0.01 millivolts. Power supplied to the potentiometer, zero adjustment, sensitivity and other factors requiring a high degree of consistancy for good instrumentation were checked at each transducer calibration or test. Proper voltage dividers were used for transducer outputs greater than the normal span of the indicating potentiometer. Transient signals, such as stray AC pickup by connecting leads and as low as 5 microvolts appeared as noise, both visible and audible, on the potentiometer and were studied in detail on an oscilloscope. Monitoring transducer output during coolant flow tests proved an excellent way of determining coolant flow cavitation in cooled flush diaphragm transducers.

b. Cooling Provisions

The closed circuit cooling system, shown schematically in Figure 34, used distilled water, clear of contaminants, as a working fluid and was designed to provide a coolant flow of 0.1 lb sec^{-1} at 500 lb in^{-2} supply pressure for 1 hour and a coolant flow of

0.1 lb sec^{-1} at 1500 lb in^{-2} supply pressure for 1/2 hour. Except for vent valves on the nitrogen gas side of the system, all plumbing and tankage was fabricated of stainless steel and thoroughly cleaned and passivated at installation. A glass lined 80 gallon domestic hot water tank was used as a return reservoir and for coolant conditioning. Coolant distribution in the laboratory was parallel from a point downstream of the pressure vessels with control valves conveniently located at each station in the laboratory evaluation procedure. Destructive coolant pressure testing, beyond the pressure capability of the coolant system was accomplished by hydrostatic test.

Coolant filtering was provided for at several points in the system and coolant replacement was determined by fluid discoloration. Fluid transferred from the reservoir to the high pressure tanks was filtered by large area cartridge type Purolater filters designed to trap particles of 25 microns absolute size. Coolant leaving the pressure vessels passed through Republic filters which employed spring loaded sintered stainless steel cups to trap particles of 2 micron nominal and 25 microns absolute in size. At 100 to 150 lb in^{-2} pressure drop across the filter, the filter cup-spring configuration was designed to lift and provide free flow. Routine cleaning avoided this and the possible resulting surge in coolant flow. Coolant was again filtered at the transducer inlet with Circle Seal in-line filters which had elements capable of removing particles of 2 microns nominal and 25 microns absolute in size. These filters were back-flushed, acid-cleaned and passivated when coolant pressure drop across them reached 75 to 100 lb in^{-2}. The in-line filters remained with the transducers through the evaluation, including proof testing in the rocket thrust chambers.

2. Dynamic Testing

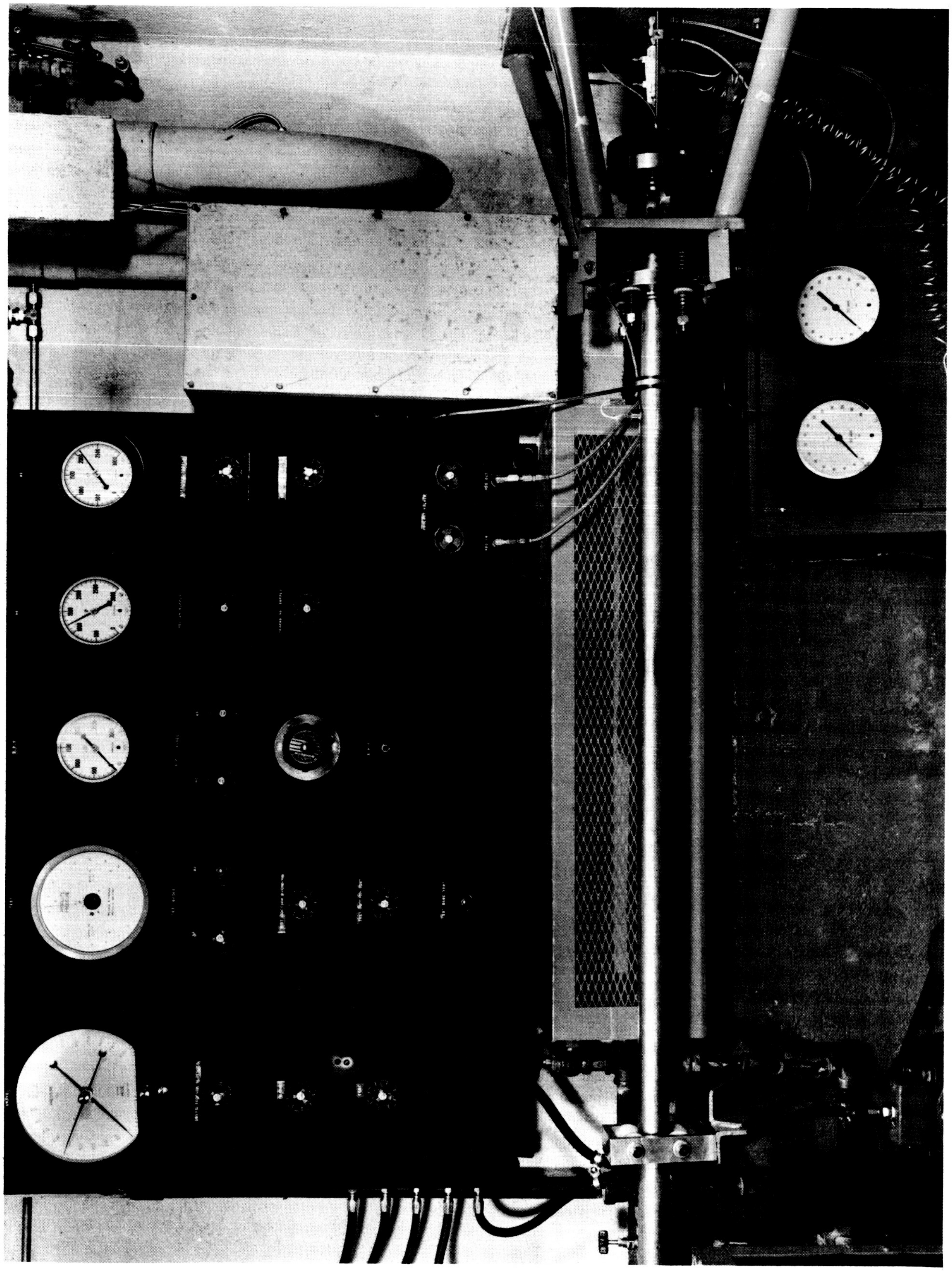
a. Shock Tube

The shock tube, seen with its control panel in Figure 35, had a drive section length of 6 feet, an equivalent length of test section and a bore of 1.66 inches. Made of 305 stainless steel extra heavy wall tubing, the tube was mounted freely on spring loaded nylon rollers with a special spring suspension and a longitudinal spring shock absorbtion-nylon braking disk system at the test end. This type of suspension eliminated high amplitude ground shock from transducer output data leaving only transducer acceleration response, a desired piece of data in transducer evaluation.

Shock tube design, discussed in Appendix D, provided a sustained pressure level of more than 4 milliseconds at approximately 440 lb in^{-2} gauge. This was considerably more than ample time to collect data for analysis to determine transducer dynamic response to a shock input and the closely repeatable step provided for excellent comparison of the various transducers evaluated in this manner. Shock tube operation and computer analysis of shock tube data are also discussed in Appendix D and will be omitted here.

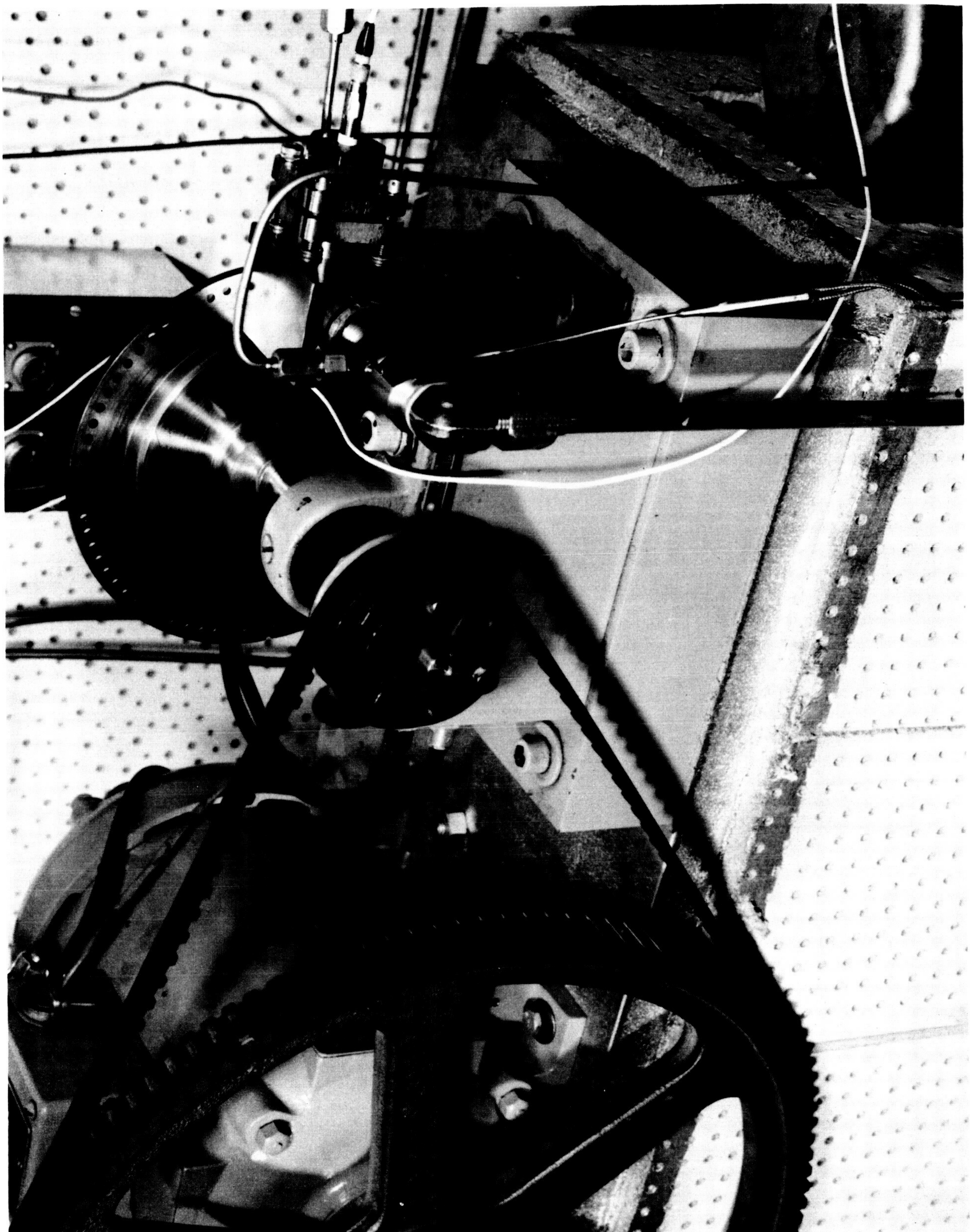
b. The Princeton Sinusoidal Pressure Generator

The design and operation of the Princeton Sinusoidal Pressure Generator shown in Figure 36, is discussed in Appendix E. This pneumatic device was conceived by H. B. Jones, a principal investigator in Transient Pressure Measuring Methods Research at Princeton. A machine



Photograph of Shock Tube and Control Panel

FIGURE 35



Photography of Princeton Sinusoidal Pressure Generator

FIGURE 36

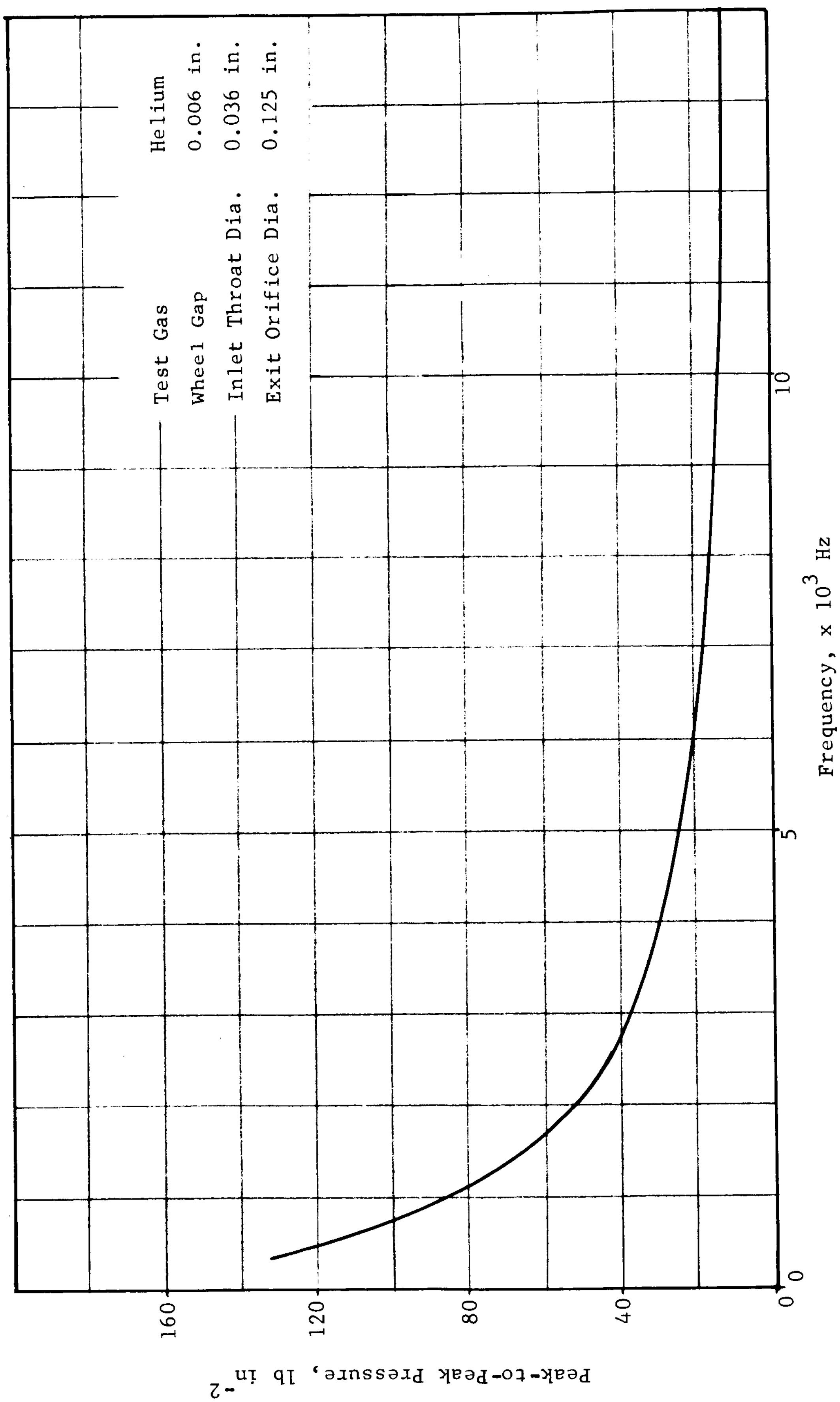
of preliminary design, constructed and studied in detail (14), was under constant improvement throughout the research. Peak to peak pressure oscillation values with increasing frequency from the latest version of the SPG are plotted in Figure 37. The transducer used for monitoring transducers undergoing evaluation in the SPG was the Kistler 601A which, at the time had a natural frequency of 140,000 Hz.

Pressure waves, generated in the SPG, were essentially sinusoidal up to 10,000 Hz. The decrease in peak to peak pressures with increasing frequency is due mostly to a balance of gas flow through the holes in the perforated wheel and the clearance between the wheel and the test chamber outlet. All transducers were evaluated up to a minimum of 10,000 Hz at an average steady state chamber pressure of 250 lb in^{-2}. An increasing average steady state pressure gradient (approximately 5 lb in^{-2}) was experienced as frequency was increased from 500 to 10,000 Hz.

Transducer outputs from the SPG were treated as shown in the instrumentation block diagram of Figure 38. An effort was always made to match transducer outputs, since electronic filter characteristics differ with varying amplitude and frequency. Properly amplified to match the monitor transducer output, switching signals to read-out instruments through the same conditioning filter eliminated taking filter characteristics into account when reducing data. Signal conditioning, instrumentation and data analysis are covered in detail in Appendix E .

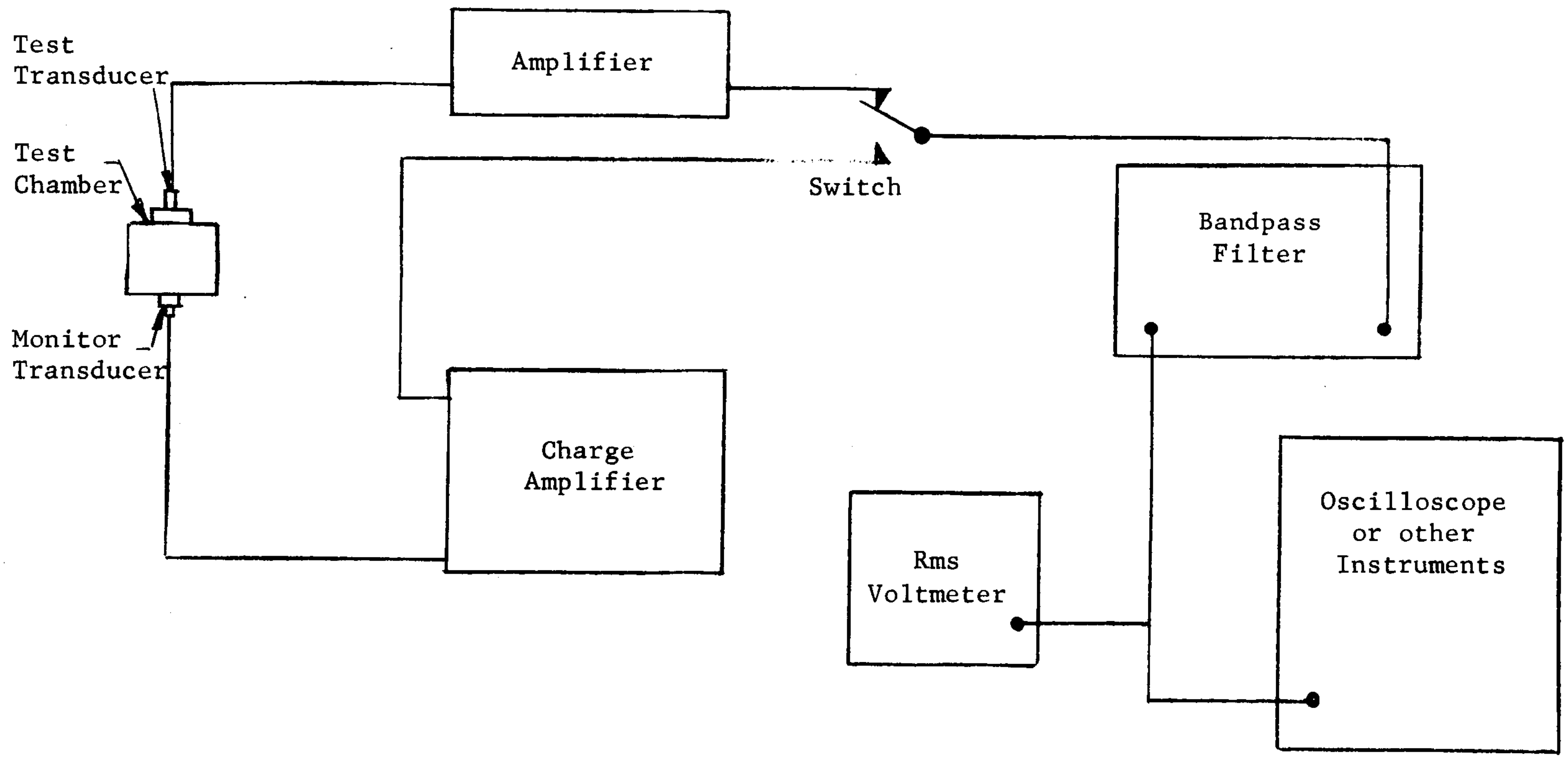
B. Rocket Test Stand Evaluations

The value of laboratory transducer evaluation is appreciated in the study of transducer characteristics, transducer design and essential



Peak-to-Peak Pressures vs Frequency for Princeton Sinusoidal Pressure Generator

FIGURE 37



Sinusoidal Pressure Generator Instrumentation Diagram

FIGURE 38

calibrations of transducers which show promise as transient pressure measuring instruments for service in rocket thrust chambers. However, only repeated proof testing in a rocket thrust chamber, under extreme operating conditions, can qualify a transducer.

1. Thrust Chamber Pulse Tests

a. Cold Pulse

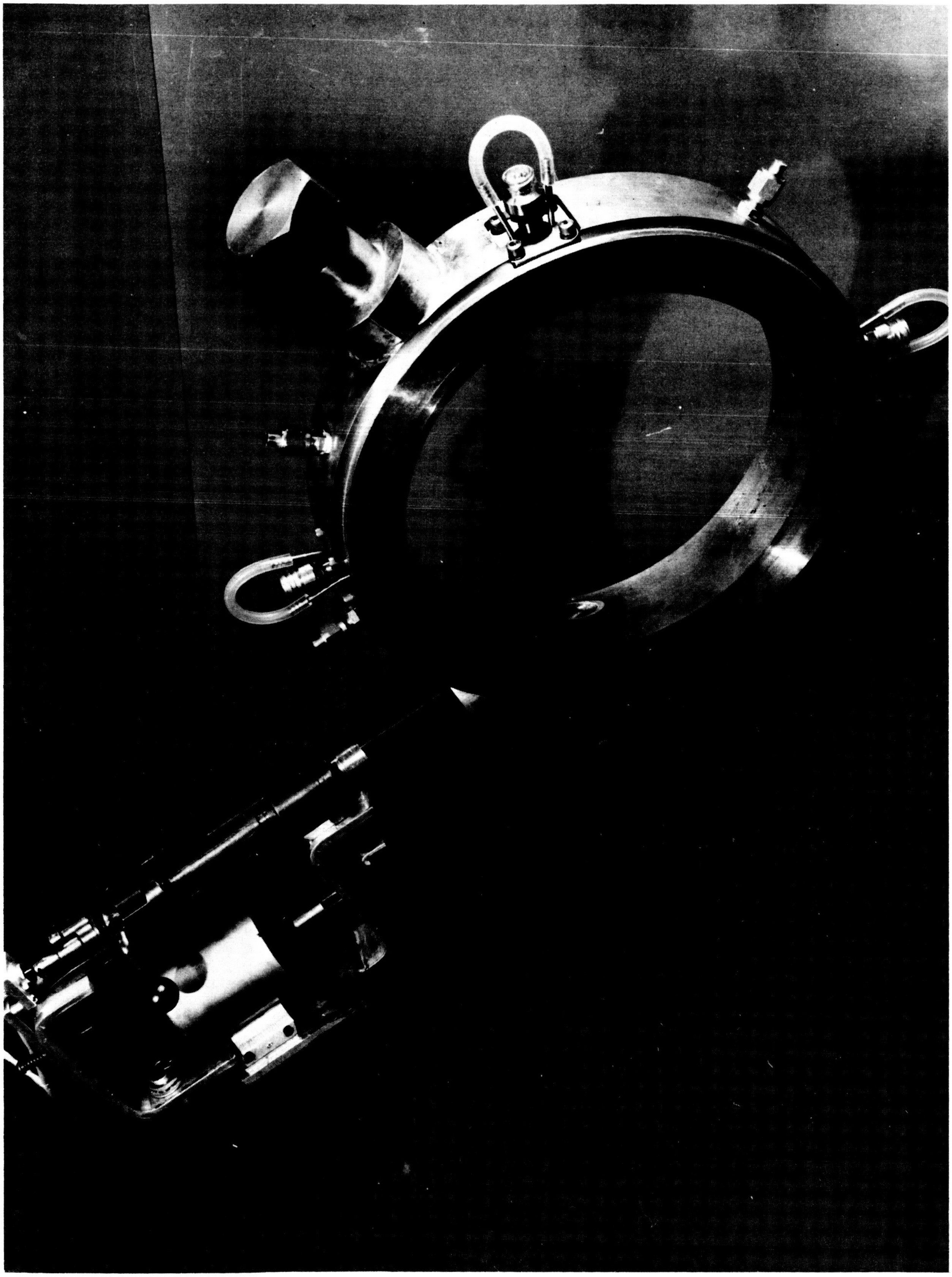
Pulse tests, using pressure bursts of mechanical devices, explosive charges, or a combination of both, provide additional information on the dynamic behavior of pressure transducers. The device used at Princeton for pulse testing is shown in Figure 39. Cold pulse tests, in which the device is discharged into an empty thrust chamber, assess transducer ability to register and recover from shock inputs when installed in position to monitor transient pressures during an actual rocket motor test.

b. Hot Pulse

Shock input from a hot pulse is seen at the start of combustion instability in the rocket motor test data previously shown. Expanding this section of data, by fast recording of a slow playback of taped data, comparison of transducer performance under "hot" conditions can be made with performance as determined in the laboratory.

2. Proof Tests

Rocket motor tests, under conditions of fully developed combustion instability are the final proof test for a transducer. Thermal drift, response to a hot shock input, dynamic response to the hot pressure oscillations, comparison of various types of transducers and heat transfer capability can be determined only by extensive testing in



Photograph of Rocket Thrust Chamber Pulse Device

FIGURE 39

a rocket motor. Although many rocket tests were made during the course of this research, no particular transducer experienced enough testing, especially at high heat flux conditions, to be fully evaluated. Some statistical data is found in Reference (11).

In addition to the work discussed thus far, evaluations were performed at Princeton for other researches especially in the area of passage connected transducers. Attention is directed to the List of Publications found in Appendix B with special attention directed towards the Response Testing of the Rocketdyne F-1 Thrust Chamber Pressure Measuring System (12).

Upon the conclusion of this research, the Transducer Laboratory Evaluation Equipment was removed at the direction of NASA Headquarters to Battelle Memorial Institute, where a program establishing a transducer evaluation capability was initiated (13).

IV. TRANSDUCER SYSTEM CONSIDERATIONS IN TRANSIENT PRESSURE MEASUREMENTS

A. Installation

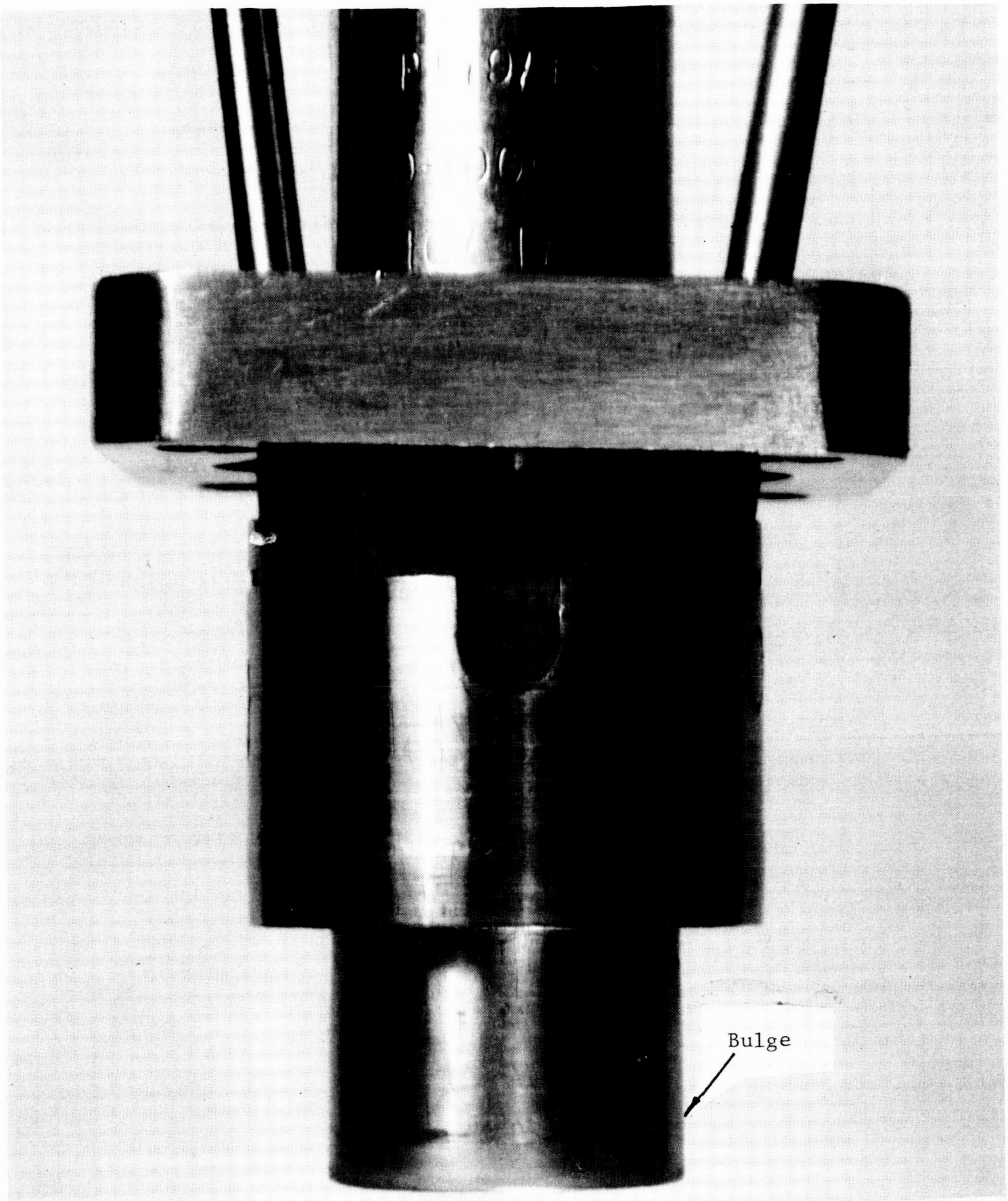
All pressure transducers are delicate instruments, no matter the degree of ruggedness built into the transducer body and its appurtenances. Pressure sensing elements, coolant fittings, electrical connections and transmission cables are easily damaged in handling. The correct amount of torque, properly applied, is essential in preserving the integrity of the transducer, its receptacle and the selected pressure seal.

1. Mechanical

a. Sealing and Gaskets

The problem of adequately sealing against high pressure oscillations at elevated temperatures is a difficult one. A type of seal or gasket was sought which would satisfy all transducer installations where minimum size was prescribed by target characteristics set forth for cooled flush diaphragm transducers.

Since gasket loading is determined by transducer retaining torque, solid gaskets of metal, high temperature plastics or a combination of both, are very limited. The transducer of Figure 40 was damaged while trying to seal a leak during a static pressure test in a research rocket thrust chamber. The bulge seen in the transducer, between the retaining flange and the gasket flat, shows a yield to column action. The seal, in this case, was a folded, copper coated, soft iron gasket designed for use on aircraft engine spark plugs. The leak may have been caused by dirt, a minor nick or scratch on the gasket surface, or torque unevenly applied to the retaining screws. Later models of this trans-



Photograph of Dynisco Model PT49CF-2M Transducer
Damaged by Excessive Applied Torque

FIGURE 40

ducer were provided with ruggedized bodies which showed little if any improvement as seen in the Zero Output vs Applied Torque curve of Figure 41.

The special spiral wound gasket* was designed about the loading provided by the four 10-32 retaining screws of a flange mounted Dynisco model PT49 transducer. The spiral wound gasket had been used successfully in industry in a wide variety of sizes and materials for over 50 years. Attention was also drawn towards this seal by its excellent performance in the variable length thrust chambers of the research rocket motors at Princeton. When properly constructed with well chosen materials, the gasket serves as an expansion joint and the spiral configuration of metal wrap with a pliant filler provides a labyrinth seal which virtually eliminates leaks due to slight irregularities in gasket surfaces. The spiral maze in the Flexitallic gaskets designed for use with the Dynisco model PT49 transducer is approximately 16 inches long.

Gaskets were supplied in thicknesses of 0.062, 0.100 and 0.125 inches to provide flush mounting and recessing the PT49 diaphragm up to 0.062 inches. Although sealing against 2000 psi at ambient temperatures was realized at 20 in-lb of torque on each screw, all Flexitallic gaskets were loaded to deflect a designed 0.010 inch at 30 in-lb on each screw. It was found necessary to apply torque evenly and at increments indicated in Figure 41. Performance in the laboratory, at ambient and liquid nitrogen

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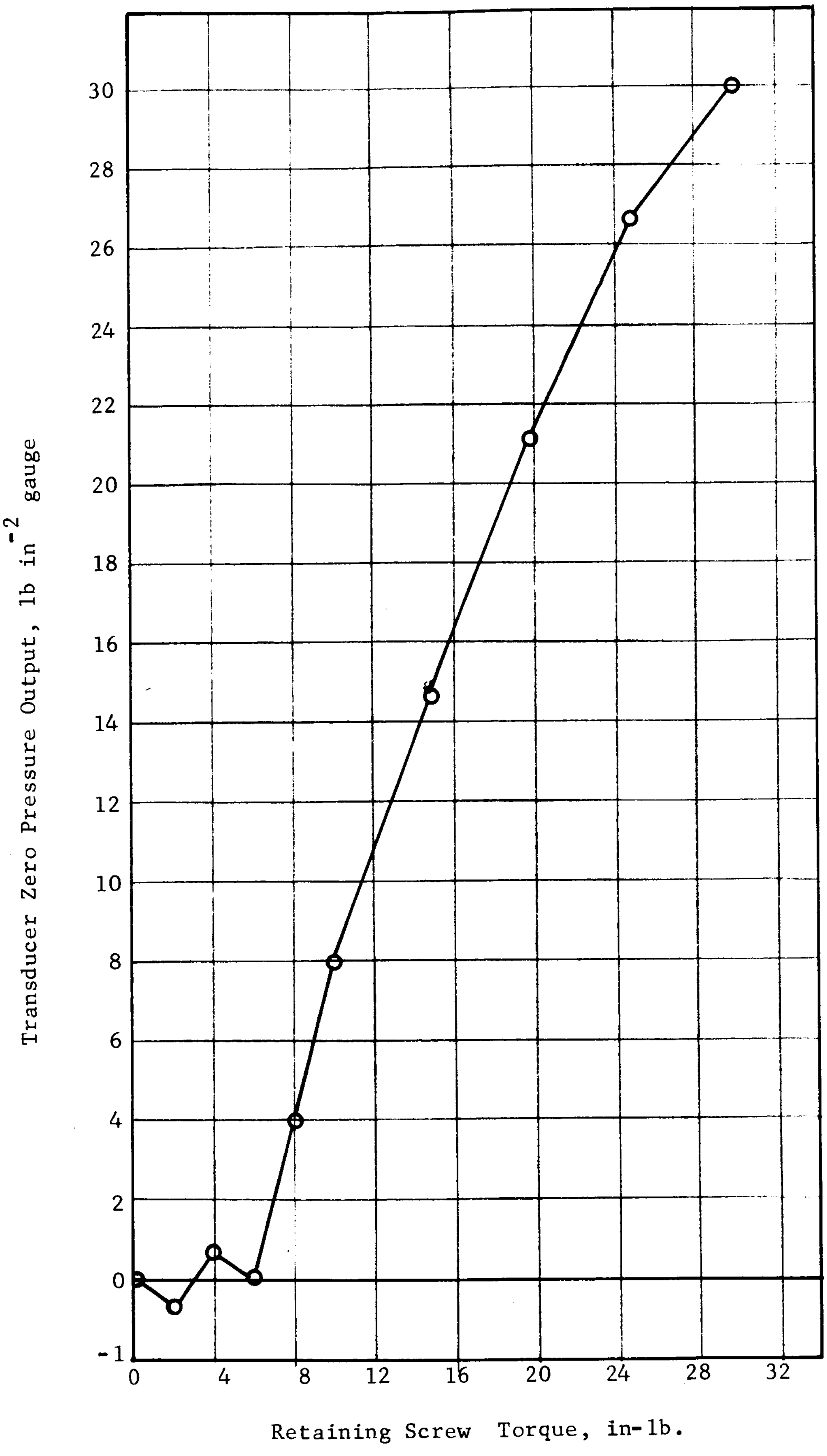
*Flexitallic Gasket Company, Camden, N. J.



Transducer Zero Output vs Applied Torque
Dynisco Model PT49CF-2m Serial No. 21208

FIGURE 41

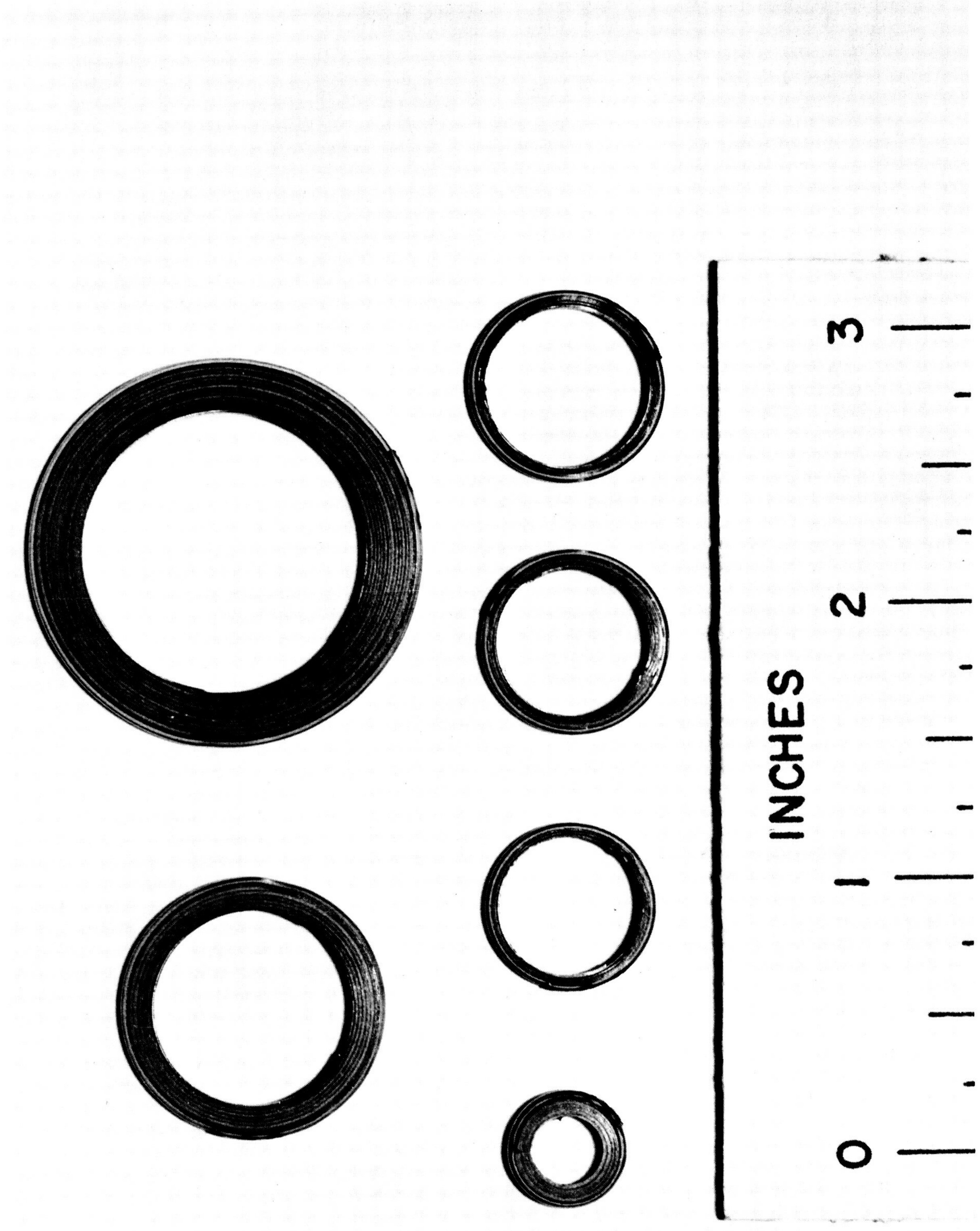
temperatures, and in the rocket motors was excellent for all tests with zero leakage recorded. Gaskets of 0.437, 0.500 and 1.000 inch nominal diameter, designed about the loading from allowable torque on the Kistler 616A, Dynisco PT134, Photocon 200 and Photocon 352A-4925 transducers, performed as well. Gaskets were replaced only when transducers were installed in the rocket motors.

A display of Flexitallic spiral wound gaskets, previously published, is shown again in Figure 42. From right to left on top are the Photocon 352A-4925 and the Dynisco PT49 gaskets. In the same order on the bottom are the Dynisco PT134, Kistler 616A. Elastronics EBL6009 and a 0.250 inch nominal inside diameter provided by Flexitallic in that company's effort to meet cooled flush diaphragm transducer target characistics. Material selected for the latter was beryllium - copper wrap with a teflon filler. No transducers were available for these gaskets and they were sent to NASA-Lewis Research Laboratories for possible use with the Electro Optical Systems PT15C transducers which had the mounting thread increased from 10-32 to 1/4-28 thread.

b. Connections

(1) Coolant

Various methods of attaching coolant tubes and fittings to the transducer body have been used. The PT134 transducer has the coolant tubes recessed and silver-brazed into the body with female stainless steel fittings to meet target characteristics. Although their design served well through extensive testing in the laboratory and through several rocket motor firings, silver-brazed joints are not recommended since only the braze fillet can be seen and there is no assurance of complete



Photograph of Various Flexitallic Transducer Gaskets

FIGURE 42

fusion in the recess. Another problem with silver-brazing is that the braze material may penetrate the joint and partially clog the coolant passage. The coolant tubes are heliarc welded to the bodies of the GL029 and the 616A assemblies. Currently, this method of attachment is considered to be the sturdiest and most reliable. The male flare fittings of the 616A are also silver brazed and do not conform with the target characteristics. Female flare fittings were always requested for coolant tubes on all transducers to insure that personnel would not place a torque load on the fixed coolant tube when attaching coolant lines and accessories.

(2) Gas Bleeds

Gas bleed assemblies should receive the same design and installation considerations as coolant tubes. Neither the silver-braze joint or the slender gas bleed tube of the HBX series of transducers, for instance, offer enough resistance to vibration or rough handling.

2. Electrical

a. Connectors

Deterioration of transducer electrical connections, caused by water or corrosive vapors and mechanical fatigue, results in spurious signals which do not necessarily appear during continuity or other electrical checks. Once electrical connections are thoroughly cleaned and dried, they can be kept so by potting, sleeving or a combination of the two. Transducer assemblies which had the connections cleaned with freon solvent in an ultrasonic cleaner and dried in a vacuum oven were assembled and tested in a dry box whenever possible. Expanded polyethylene tubing, filled with silicon rubber compound, covered the connection and a short section of the armored signal lead. Shrinking the polyethylene tubing with heat forced out the excess silicone rubber which was trimmed or removed after curing. This treatment, considered necessary for piezoelectric transducers, survived all laboratory and rocket motor tests, including submersion of the GL029 in water.

The mechanical design of transducer electrical connectors should provide for more than adequate pin contact area and a method of locking mating parts. It is also advantageous to have the connectors placed at the end of a very flexible armored cable, relieving the weight and overall length of the transducer, a consideration to be given when high accelerations and vibrations are present. The armored cable on the Dynisco Model PT134 was found to be too rigid and not long enough to provide adequate support free of the hot rocket combustion chambers.

b. Cabling

Transducer output signal cables should be low noise, shielded cables, continuous and with a minimum of connectors between transducer and recording instruments. When connectors are necessary, they should mate without a third piece to provide a union and protected by sleeving against moisture or other corrosive media. Cables should be matched to output signals and calibrations should include the actual cable length and connectors.

B. Excitation

Wire resistive strain gauge transducers are quite large and readily accomodate temperature compensating resistors and a source of constant voltage only is necessary to excit the transducer. A sensitivity of 3 millivolts per volt excitation is more or less standard and a number of power supplies with low ripple are commercially available. In many cases batteries will suffice to provide the required constant 10-20 volts.

Piezoresistive strain gauge bridge transducers are quite small which makes compensation for sensitivity changes, due to change in temperature, difficult within the transducer and a source of constant current excitation is required. However, for very small temperature changes, a constant voltage source of excitation will suffice. Power supplies which operate in both constant current and constant voltage modes are available. For constant current operation, the supply must be located near the transducer or feedback wires run as near as possible to the transducer input connector pins for fast compensation.

Transducers employing variable capacitance as a method of transduction require a power supply to provide an RF carrier and feedback circuit to relieve the effects of cable capacitance as well as a demodulator to provide a full-scale direct-current output.

Piezoelectric transducers do not need a power supply as such but do need special circuitry and amplification to convert the small charge from the piezoelectric crystal to a significant usable output signal. The small charge is protected from leakage by taking installation measures previously described.

C. Signal Conditioning

Final conditioning of transducer output signals will vary depending on transducer sensitivity, integrity of cables and connectors and display or recording instrumentation.

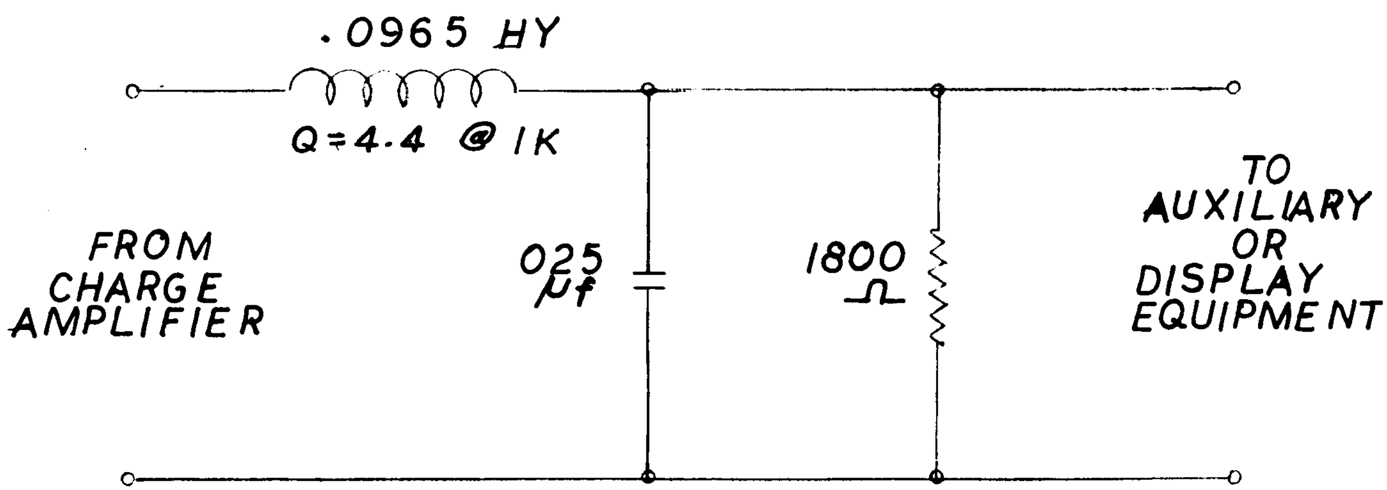
1. Amplification

Amplifiers used to provide usable signals or driving power for recording instruments should be well stabilized with a flat gain vs frequency curve across the range of frequencies a transducer will encounter for a given set of data. Even so the amplifier characteristics should be known exactly so that data may be corrected.

2. Filtering

Filtering unwanted frequencies, such as 60 cycle noise from nearby electrical power system or transducer resonant frequency, may be desirable. Amplifiers and display or recording instruments with limited frequency response may satisfactorily remove low frequencies or reduce them to negligible amplitude. Band-pass filters, either fixed or adjustable, may be used to filter out unwanted frequencies especially when a fundamental frequency is to be studied or where a narrow band of frequencies is of interest. Filtering out the steady state pressure or d-c component of the signal with a simple R-C network of one or more stages will permit greater expansion of transient data on recording equipment. The steady state data can be placed on an accurate low-response recorder.

It is practical to design a filter with characteristics to compensate for increase in amplitude as a transducer approaches its resonant frequency (8). Figure 43 is a schematic of the circuit used for dynamic compensation of a small passage technique device. Its characteristic curve at optimum trimming is seen in Figure 23 along with transducer output with and without dynamic compensation.



Schematic of Dynamic Compensation Filter
for AGC Model HB3X Transducer

FIGURE 43

D. Calibrations

Calibration of transducer systems beyond the laboratory evaluation of a transducer, as described in Section III, are quite necessary for good data acquisition and reduction. As previously stated, the performance characteristics of signal conditioning equipment must be known. These, however, should be determined in-line with transducer accessories, cables and connectors and the instruments to be used for data acquisition. At the same time, electrical interference, ground loops, impedance mismatching and other instrumentation problems which may exist can be found and corrected.

For accurage reduction of steady state data, gathered from flush mounted transducers, transducer zero stability as affected by heat flux and coolant pressures must be determined in the laboratory and properly applied.

Where non-linearity and hysteresis exist significantly, transducer sensitivity at the pressure level of data acquisition must be used for data reduction. Transducer response to transients at various average pressure levels is yet to be investigated.

E. Display and Recording

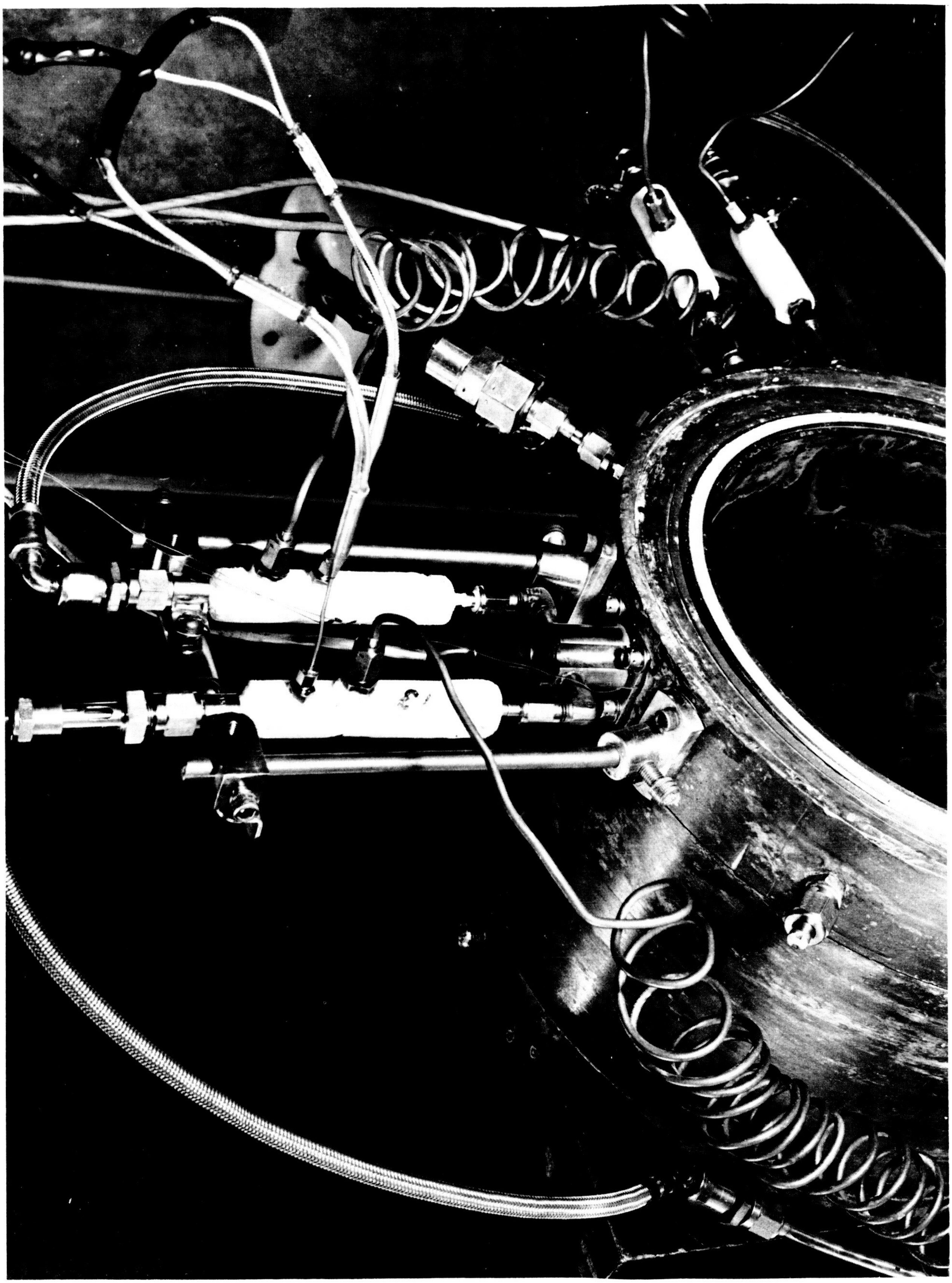
A very prominent and probably the most convenient method of transient data storage is the magnetic tape recorder. Data, recorded at high speed, can be played back and recorded on an expanded time scale for detailed analysis of component frequencies and corresponding amplitudes, wave form and phase relations. Data playback may be placed on a Panoramic analyzer or oscilloscope to be photographed, or on the photosensitive paper of an oscillograph recorder. Data may also be placed on cards with the appropriate calibration factors for computer analysis.

V. OPERATIONAL CONSIDERATIONS IN MEASURING TRANSIENT PRESSURES IN LIQUID PROPELLANT ROCKET THRUST CHAMBERS

A. Location and Mounting

The location of transducers in a rocket thrust chamber must be determined on the basis of both requirements for data and the ability of each one to withstand local conditions in the chanber. Hot spots caused by injector patterns with a resultant variation in mixture ratio and combustion gas composition must be avoided. Recessing the transducer slightly (1/32 inch or less) to assure that no portion projects into the chamber is recommended as a means of reducing heat transfer to the instrument, although too large a recess will have the opposite effect and the signal will be deteriorated as well by frequencies related to the dimensions of the cavity.

Diaphragm size of a transducer often limits its location with thickwalled uncooled chambers presenting the widest choice. Figure 44 shows two Dynisco PT49CF water-cooled transient pressure transducers mounted in a research rocket thrust chamber in the same section but placed 90° apart for the identification of instability modes. An uncooled transducer (Dynisco PT76) is shown installed between them on a short length of tubing for the relatively precise measurement of average chamber pressure. Whereas, the sensing point for this steady state measurement is usually a small diameter hole drilled in the chamber wall leading to a standard tubing fitting on the outside wall, the transient pressure transducers with their large diameter diaphragms require machined holes with accurate dimensions having proper gasket seats and carefully machined threads or threaded inserts for high strength mounting screws.



Photograph of Two Dynisco Model PT49CF Transducers
Installed in a Research Rocket Thrust Chamber

FIGURE 44

Figure 45 shows a mounting configuration in a cooled chamber for a Princeton Small Passage Technique Adapter. The relative ease with which the small diameter passage can be located through (or between) coolant tubes is a major benefit of the technique.

As discussed in Section IV above, it is essential that proper gasketing be employed so that the transducer will remain tightly sealed through startup and shutdown, pulsing and bombing and high amplitude combustion instability for a number of operations of the thrust chamber. The external environment during either test stand or flight operation must be considered in locating and mounting a transducer and protection must be provided as necessary for cabling and other connections as well as for the transducer.

B. Startup and Shutdown

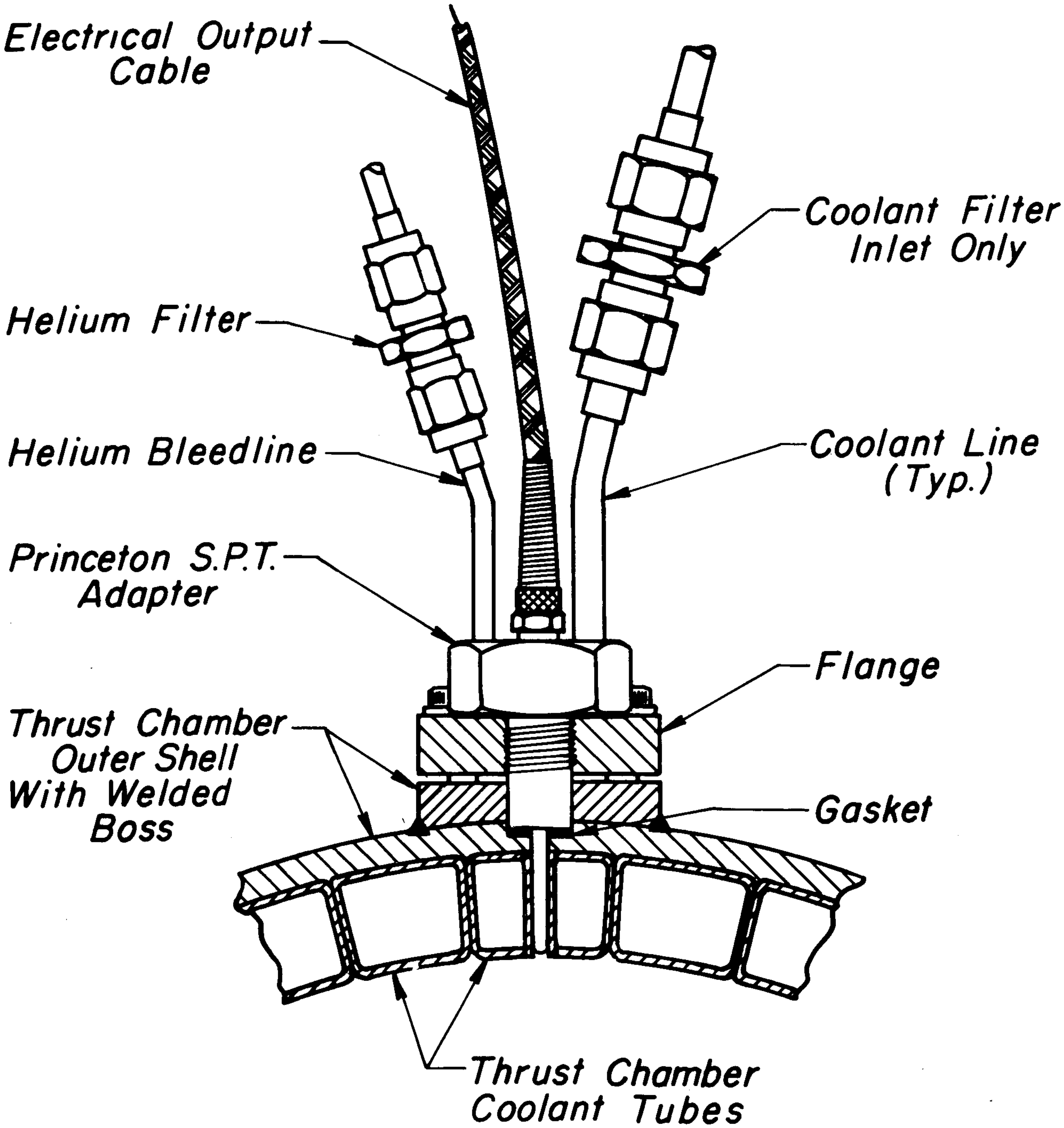
Rates of pressure rise and fall are very often high during transient conditions and the thrust chamber usually experiences rapid variation in mixture ratio and temperature.

During startup high vibrational accelerations of both the thrust chamber walls and any transducer mounted thereon(from the sudden ignition of the propellants)can result in failure of the transducers. Also, thermal shocks and rapid heating can cause drift of zero and sensitivity in the transducer output.

Although shutdown ordinarily represents a less strenuous condition than startup, roughness and mixture ratio variation can damage transducers so they should be carefully inspected for damage prior to the next operation.

C. Pulsing and Bombing

The technique of pulsing or bombing an operating rocket



Drawing of Princeton Small Passage Technique Adapter
Installed in a Cooled Rocket Thrust Chamber Wall

FIGURE 45

thrust chamber to assess its stability is widely accepted and actively practiced during research and development testing of liquid propellant rocket motors. This is a severe requirement for many transducers because the thin, cooled diaphragms are susceptible to damage from shock over-pressures and concentrated high temperatures. Flame shields are often employed, although they must be carefully designed to maintain adequate dynamic performance. The use of a multi-hole flame shield generally requires an enlarged diameter opening in the thrust chamber wall which is undesirable. A single short connecting passage can sometimes be used if it is carefully designed to retain an adequate dynamic response and its volume and resonance do not lead to "pumping" hot combustion gases along the passage.

Protective coatings for transducer diaphragms composed of ceramic or ablative material are promising approaches to the solution of this problem. Porous diaphragms with coolant flowing through them, to replace the gas films removed by pressure wave action, may possibly be used.

D. Combustion Instability

Fully developed combustion instability, especially in the spinning high frequency modes, represents the worst condition that the transducers must withstand. The steep wave fronts with accompanying pressure and temperature fluctuations and the scrubbing action of the high speed gases require the utmost protection for the transducer sensing element while at the same time it is necessary not to distort its capability for accurate measurement of the details of the pressure variation.

Since combustion instability often continues for a large number of cycles, problems of material fatigue are often encountered in addition to the difficulties from the temperature and pressure excursions. It would seem that every artifice available to the transducer designer and developer must be employed and thoroughly tested to provide a satisfactory solution to this problem since precise measurements during combustion instability are essential to its identification and elimination.

E. High Heat Transfer

A section on high heat transfer is presented here to emphasize that, although conditions exist that involve high heating rates to surrounding material the thin material of a transducer is best protected by thermal barriers. These barriers may consist of ablative or ceramic coatings, liquid or gas films or location of the sensitive element at a distance from the heat source. Their effect on the ability to measure the pressure with precision must be considered. It may be possible to distribute the locally intense heating by sandwich materials with layers of high and low conductivity. Refractory metals have been employed. Fabrication, and other material compatibility problems are often encountered and must be allowed for.

The heat that does get to the transducer must be conducted away so that thermal sensitivity effects are minimized and at the same time the cooling provisions should not introduce problems which cannot be dealt with by careful design. These problems include zero and other output shifts caused by coolant pressure, internal leakage, large dimensional increases, etc. Much design work and research development is needed and should be undertaken to handle this problem adequately.

F. Personnel

The most difficult problem to deal with in a definitive way relates to the training and motivation of the personnel involved in the broad problem of transient pressure measurements. Inadequate concern has been shown at all levels and much educational effort remains. It is hoped that the efforts of the past several years have highlighted the need for these measurements and the proven hardware required to make them with satisfaction; however, it has been made very clear that the best efforts can be negated unless operating personnel are properly trained and motivated. This is especially true when a new or advanced instrument is introduced that requires altered treatment and handling. Still this is only the final link in a chain that has had far too little attention.

VI. CONCLUSIONS

The measurement of transient pressure in rocket motors has in the past been largely unsatisfactory at best. This situation is related to a considerable number of factors, including a lack of understanding of the importance of accurately measuring dynamic factors in the research and development of high performance rocket systems, widespread ignorance of the fundamentals of the dynamic response of mechanical and fluid systems, traditional neglect of research, development, evaluation and test of instrumentation to meet a special measurement requirement and only a modicum of interest among sponsors, manufacturers or users to undertake their responsibilities. At the present time the situation is little changed, although some signs of awakening - similar to those of a cloudy mid-March day - are evident and there can be only hope for the necessary changes in the future.

Initiation of the necessary changes should come broadly from within the scientific and technological community and several committees are at work in the wide and narrow pathways of concern. However, since funds are fundamental, government agencies must necessarily provide essential and hopefully, interested and understanding support. The problem can no longer be left to grow at the doorstep of special instrument manufacturers who are usually small concerns with comparatively limited resources.

Basic research is needed on the fundamentals of transduction methods especially in materials. Applied research is required on heat transfer and flow in torturous passages. Advanced development of electronic, thermodynamic and mechanical elements of specific design configurations must be undertaken. Such aspects as gasketing must receive attention. Advanced technology needs to be applied to problems of fabrication and economical production. A major educational and indoctrinational problem also exists among workers of high and low estate.

Efforts must be made to identify both general and special metrology requirements ahead of the need so research, development, evaluation and test activity can be completed and transduction system elements of established performance can be made available at reasonable cost. This will require a greater coordination of efforts and infusion of funds than that practiced in the past.

An overall upgrading of the aerospace instrumentation field is needed in many areas and this represents a challenge that is appropriately made to higher education as well as government and industry. It is earnestly hoped that the call will be heeded.

VII. RECOMMENDATIONS

A. General

1. It is recommended that coordinated efforts be made to recognize the need for transient pressure measurements in the high performance rocket and other advanced propulsion systems of the future and that these needs be interpreted in the form of target characteristics and specifications.

2. Development, evaluation and test efforts should be merged to provide transduction and other instrumentation system elements of proven capability. Although this will require the direct expenditure of greatly increased funds, these efforts will result in an overall economy in time and money of much greater magnitude by improvement in the orderliness and cost of future system development.

3. A rather major effort at several scientific and technical levels should be made to educate workers in the aerospace propulsion field concerning the realities of dynamic performance of instrumentation systems on the one extreme and the handling requirements when using high response instruments operationally on the other.

B. Specific

1. A miniature, cooled flush diaphragm transient pressure transducer should be developed, evaluated, tested and made available at a reasonable price for use according to the target characteristics presented in the text or specifications derived therefrom. The transducer described is believed to represent a possible compromise of desired and realizable characteristics that would find wide usage during research and development testing and in flight.

2. Further efforts should be made to develop laboratory evaluation

techniques and to correlate them with test stand behavior.

a. Further development of dynamic performance evaluation equipment, including shock tubes, sinusoidal pressure generators, etc., is needed.

b. The development of very high heat source testing equipment is badly needed.

c. Funds should be provided specifically for the rocket motor tests necessary to correlate the laboratory evaluations and for the development of proof and other instrument tests that can only be accomplished during the firing of an actual rocket motor.

d. Centers should be evaluated within the government and elsewhere for the evaluation of transducer system dynamic performance.

3. Design and development competitions should be engaged in with incentives according to performance. Development should be pursued until a fully tested transducer is in production at a reasonable price. Quantity purchases should be discouraged while the transducer or other system elements are in a partially developed status.

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APPENDIX C: JP24 Laboratory Evaluation Procedure for Current Water-Cooled Flush Diaphragm Transient Pressure Transducers

Type of Transducer: ______________________________

Manufacturer: ______________ Model: ____________ Serial: ____________

Other Data: ______________________________

Requested by: ______________ Conducted by: ______________

Approved by: ______________________________

Date Start: ______________ Date Stop: ______________

A. Inspection	Initial Time Date
1. Inspect transducer, especially for flaws or damage with a stereo-microscope and Zyglo as necessary, noting cracks, dents, imperfect welds, etc. (Attached photos or sketches as required). ______________________________ ______________________________	
2. Measure transducer for compliance with outline drawing. Note deviations: ______________________________ ______________________________	
3. Measure leakage resistance from all active pins to ground using the volt-ohmyst. Leakage resistance = ____________ megohm.	
4. For strain gage type transducers, measure resistances using the Wheatstone bridge. Input resistance = ____________ohms. Output resistance = ____________ohms.	

B. Coolant Testing	Initial Time Date
1. Install transducer in static test system in accordance with instructions dated 2 June '64 for coolant flow tests and static pressure calibrations. Use Δp- ΔT fittings, coolant inlet filter, coolant outlet sight-glass, and selected gaskets.	

N.B. These fittings are to remain on transducer throughout the evaluation. Connect transducer to instruments and auxiliary equipment. Follow manufacturer's procedures for the adjustment of auxiliary equipment and allow recommended warm-up time.

Transducer gasket ______________ Adapter gasket ______________

Δp- ΔT Set No. ____________ Max. Torque ____________ in. lb.

Torque, in. lb.	0									
Output, mv										

Auxiliary equipment, Serial No(s) and control settings ________

____

____

2. Attach coolant and instrumentation lines for coolant flow rate vs pressure drop test at rated average coolant pressure of __________ psig.

Flow Meter Serial No. ______________. Flow Meter Constant _____

P_{in} psig	P_{out} psig	ΔP $P_{in}-P_{out}$	Coolant cps	Flow pps	Transducer Output mv	Transducer Output psig	Coolant Temperature mv	Coolant Temperature ^oF
0	0	0	0	0				
0	0	0	0	0				

3.

B. Coolant Testing	Initial Time Date
3. Apply one-half rated pressure on diaphragm and repeat item 2.	

P_{in} psig	P_{out} psig	ΔP $P_{in}-P_{out}$	Coolant cps	Flow pps	Transducer Output mv	psig	Coolant Temperature mv	^oF
0	0	0	0	0				
0	0	0	0	0				

4. Reverse coolant flow by changing Δp- ΔT fittings at transducer. Repeat item 2.

P_{in} psig	P_{out} psig	ΔP $P_{in}-P_{out}$	Coolant cps	Flow pps	Transducer Output mv	psig	Coolant Temperature mv	^oF
0	0	0	0	0				
0	0	0	0	0				

B. Coolant Testing

5. Repeat item 3.

P_{in} psig	P_{out} psig	ΔP $P_{in}-P_{out}$	Coolant cps	Flow pps	Transducer Output mv	Transducer Output psig	Coolant Temperature mv	Coolant Temperature °F
0	0	0	0	0				
0	0	0	0	0				

6. Disconnect signal lead and repeat item A3. Leakage resistance ____________________.

7. Connect signal lead and leave transducer energized. Report coolant test data.

8. Tag transducer for coolant conditions as follows:

   a. Inlet Pressure ________ psig.

   b. Outlet Pressure ________ psig.

   c. Average Coolant Pressure ________ psig.

   d. Coolant Flowrate ________ lb./sec.

   e. Inlet tube as determined by items B2 and B4.

   N.B. All testing unless specifically directed otherwise, is to be carried out under the above conditions until the transducer is re-evaluated.

9. With coolant flowing observe zero reading during a one hour period at 5-minute intervals. Report any significant shift in zero.

Time of day	Output mv	Time of day	Output mv	Time of day	Output mv

C. Static Testing	Initial Time and Date
1. Completely purge coolant passages of water with dry nitrogen gas from static test panel at 20 psig max. Leave coolant lines disconnected.	
2. Apply ________psig to transducer. Insert on appropriate voltage divider to bring output on the calibrator scale. Divider ratio = _____________. Release applied pressure.	
3. Apply pressure in ________ psi steps to_____psig and return in equal steps to zero pressure. N. B. Care must be taken to approach each pressure in the particular direction of travel to avoid any masking of hysteresis or other effects. Computing identification ______________________.	

Ascending Pressure Output (mv)	Applied Pressure (psig)	Descending Pressure output (mv)
______	0	______
______	______	______
______	______	______
______	______	______
______	______	______
______	______	______
______	______	______
______	______	______
______	______	______
______	______	______
______	______	______
______	______	______
______	______	______
______	______	______
______	______	______
______	______	______
______	______	______
______	______	______
______	______	______
______	______	______
______	______	______

Ascending Pressure ⟶

Descending Pressure ⟶

N.B. Report apparent erroneous data before proceeding with evaluation.

C. Static Testing (cont'd)	Initital Time and Date
4. Establish rated coolant flow and repeat Item C3. **Make certain** that zero pressure output has stablized before proceeding. Seat transducer diaphragm. Computing identification__________.	

Ascending Pressure ↓ — Descending Pressure ↑

Ascending Output Voltage (mV)	Applied Pressure (psig)	Descending Output Voltage (mV)	
	0		

C. Static Testing (cont'd)	Initial Time and Date
5. Duplicate Item C4 to determine repeatability. Seat transducer diaphragm. Computing Identification____________.	

Ascending Output Voltage	Applied Pressure (psig)	Descending Output Voltage (mV)
	0	

Ascending Pressure

Descending Pressure

D. Dynamic Testing	Initial Time and Date
1. Vibration testing	

C-9.5

Dynamic Tests in Shock Tube

Picture No. ______________

Vert. Sens. ______________

Sweep Rate ______________

Rise Time ______________

Nat'l Freq. ______________

Picture No. ______________

Vert. Sens. ______________

Sweep Rate ______________

Rise Time ______________

Nat'l Freq. ______________

Picture No. ______________

Vert. Sens. ______________

Sweep Rate ______________

Rise Time ______________

Nat'l Freq. ______________

D. Dynamic Testing (cont'd)	Initial Time and Date
2. Shock Tube Testing a. Install the transducer in accordance with instructions dated 2 June 1964 for coolant flow and static testing. Transducer Location ________ Diaphragm Position ____________	
b. Establish coolant flow through the transducer and allow adequate warm-up time.	
c. Insert a burst disc in the shock tube and proceed according to instructions dated 5 June 1964. Test Gas ____________ Test Pressure ____________psia Driver Gas____________ Burst Disk size__________psi	
d. Photograph the oscilloscope display with the Polaroid camera and record the following information	

Date	Time	Picture No.	Vert. Sens.	Horiz. Sens.	Test Section Pressure psia	Burst Pressure psia

e. Insert ¼ inch thick steel plate between tube flanges ahead of transducer and repeat item d.

Date	Time	Picture No.	Vert. Sens.	Horiz. Sens.	Test Section Pressure psia	Burst Pressure psia

Other Data: ____

____

____

____

____

D. Dynamic Testing (cont'd)	Initial Time Date
3. Sinusoidal Pressure Generator a. Install the transducer in the generator chamber. Establish coolant flow and allow adequate warm up time. Plenim Pressure______psig Chamber Pressure _________psig Test Gas_________________Diaphragm Position______________	
b. At 1000 cps, check peak to peak chamber pressure from output of monitor transducer and average chamber pressure from both test and monitor transducers. P_c, test______psig P_c,Mon.________psig pk-pk ________psig	
c. At each excitation frequency record output level for each channel as indicated on the volt meter.	

Frequency (kcps)	Monitor Output mv	Test Output mv

E. Heat Transfer Testing	Initial Time and Date
1. Open Flame Test a. Install transducer in test apparatus and proceed according to instructions dated Diaphragm position ________________.	
b. Check coolant supply level.	
c. Ice cold junctions and check instrumentation.	
d. Establish coolant flow and allow adequate warm-up time.	
e. Prescribed operation conditions: Δ T instrument range ___________mv. Transducer body temp. _____ mv. Transducer position, D_____in. Approximate heat flux 1.5 BTU/in^{2}sec Ox gas _____ CFH, _____ psig Fuel gas _____ CFH _____ psig	
f. Get data points 1 and 2 below. Ignite torch and complete test. N. B. Hold coolant pressure throughout test.	

Data Point	Coolant Flow cps	Coolant T_{in} mv	Transducer Output mv	Transducer Output psi
1 Coolant off				
2 Coolant on				
3 Heat on				
4 Both off				

Note: Attach ΔT trace to this form

E. Heat Transfer Testing	Initial Time and Date
2. Open Flame Test	
a. Install transducer in test apparatus. Diaphragm position_____________.	
b. Check coolant supply level.	
c. Ice cold junctions and check instrumentation.	
d. Establish coolant flow and allow adequate warm-up time.	
e. Prescribed operation conditions: Δ T instrument range _____________mv. Transducer body temp.______mv. Transducer position, D______in. Approximate heat flux __3__BTU/in^2sec Ox gas ______CFH, _____psig Fuel gas______ CFH _______psig	
f. Get data points 1 and 2 below. Ignite torch and complete test. N.B. Hold coolant pressure throughout test.	

Data Point	Coolant Flow cps	Coolant T_{in} mv	Transducer Output mv	Transducer Output psi
1 Coolant off				
2 Coolant on				
3 Heat on				
4 Both off				

Note: Attach ΔT trace to this form

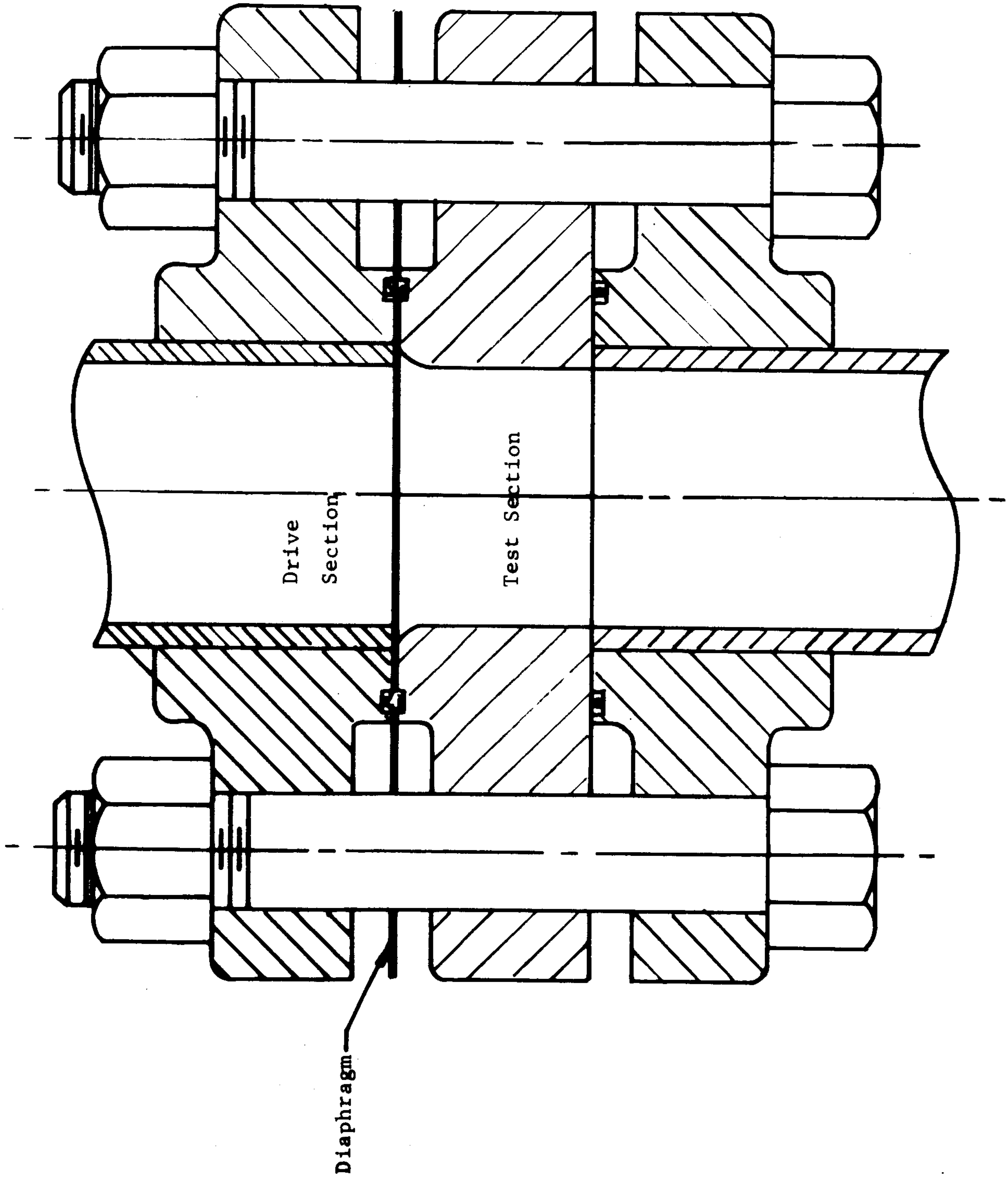
APPENDIX D: Shock Tube for Dynamic Response Testing of Transient Pressure Transducers

Dynamic testing of pressure transducers by providing a sustained pressure step input, fast enough to shock-excite the transducer and of sufficient time to obtain a record of transducer response, is best accomplished in a shock tube.

1. Design

Typically, the shock tube used for this research consisted of a straight tube divided by a rupture disk into a driver section and a test section with appropriate controls and instrumentation. Driver and test sections were made of 1.66 inch inside diameter, extra heavy stainless steel tube, 6 feet long with standard welded stainless steel flanges for end connections. Blind flanges were machined to receive the transducers with special bosses welded on the test section to accomodate side-mounting of transducers, triggering pickups and wave tracking instrumentation. All sealing was accomplished with standard neoprene O-rings.

Figure D-1 shows the diaphragm burst assembly in detail. The diaphragms were cut from the same sheet of type 1100-1114 aluminum 0.020 inch thick selected for a diaphragm burst pressure of 540 lb in^{-2} absolute. This burst pressure was uniform ($\pm$ 5psi) throughout the research and, at the proper test section pressure, provided a shock speed of Mach 3.4 to 3.8 driving helium into nitrogen gas. Uniformity in diaphragm rupture is attributed to the selection of diaphragm material, the method of admitting gas to the test section and design of the diaphragm burst assembly. The piece sup-



Shock Tube Burst Assembly

FIGURE D-1

porting the diaphragm on the test section side in Figure D-1 had a radius designed to provide a sperical burst of the diaphragm. This design not only removed sharp edges which would cut the diaphragm but also reduced the hazard of diaphragm particles reaching the transducer to an absolute minimum. In the hundreds of tests made, there was no evidence of pieces of diaphragm in the tube after rupture.

Figure D-2 is a schematic of the shock tube gas system layed out to conform with the panel illustrated in Figure 35. The orifice in the drive-section feed line is used to control the rate at which gas is admitted and hence the rate at which pressure is applied to the diaphragm. Since creep in the aluminum diaphragm is a function of pressure, temperature and time, admitting gas to the driver section at a constant rate along with provisions for a spherical burst of selected diaphragm material provided a fairly constant burst pressure.

2. Operation

The control panel seen in Figure 35 and represented schematically in Figure D-2 is divided into three sections. The section to the right is a gas distribution system designed to supply various gases to both driver and test sections. The center section facilitates delivery of bleed gases to transducer assemblies utilizing the gas bleed technique, setting test conditions in the test section prior to firing the shot and blow-down of the test section after the shot when the tube is open for diaphragm change. The section to the left provides valving for admitting gas to the drive section, venting and blow-down after the shot. All gas admitted to the control panel is filtered of particles 25 microns nominal in size and regulated to a maximum 1000 lb in^{-2} gage shock tube design pressure.

D-4 1

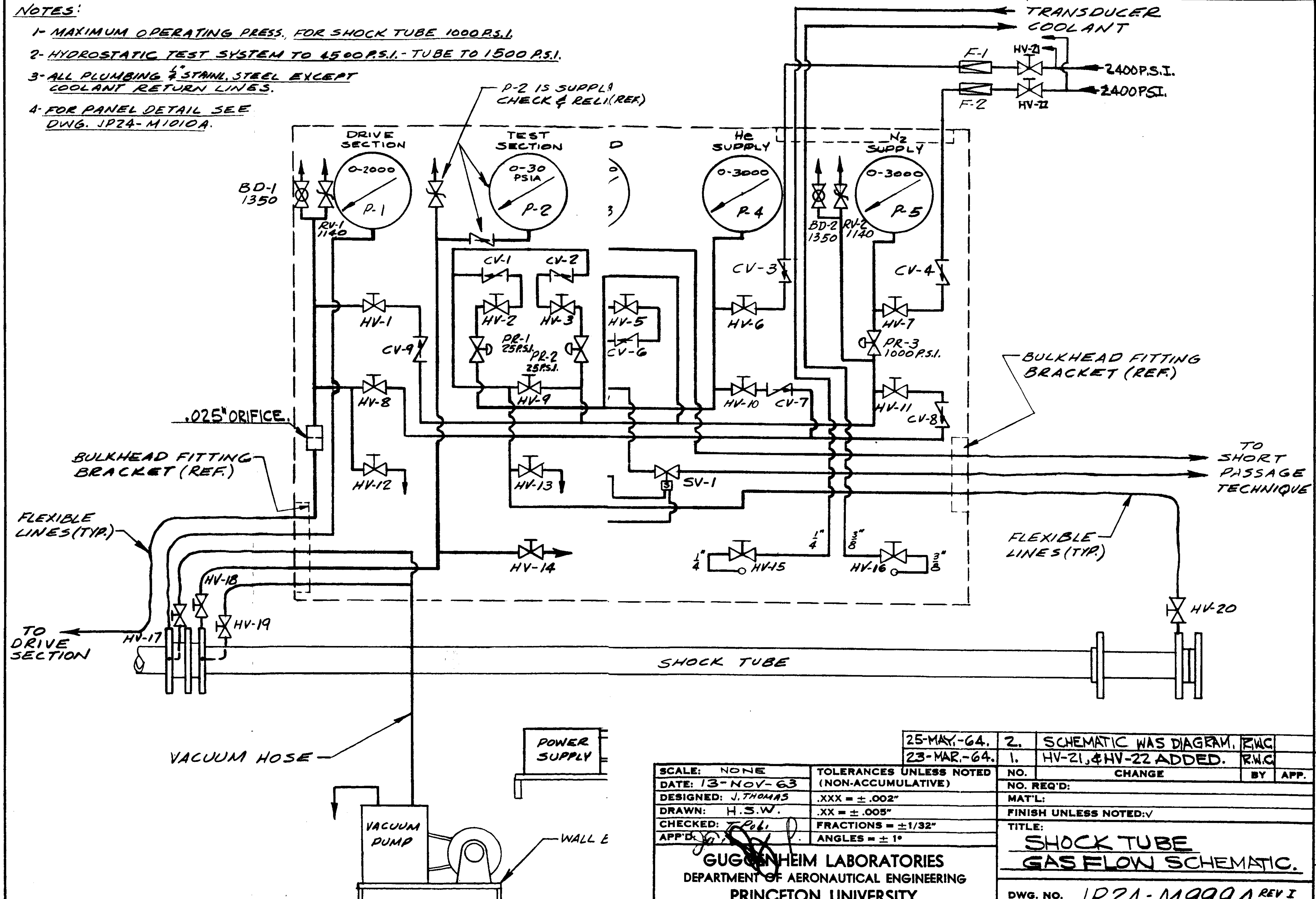
NOTES:

1- MAXIMUM OPERATING PRESS. FOR SHOCK TUBE 1000 P.S.I.

2- HYDROSTATIC TEST SYSTEM TO 4500 P.S.I. - TUBE TO 1500 P.S.I.

3- ALL PLUMBING 1/4" STAINL. STEEL EXCEPT COOLANT RETURN LINES.

4- FOR PANEL DETAIL SEE DWG. JP24-M1010A.



25-MAY-64.	2.	SCHEMATIC WAS DIAGRAM.	R.W.C.	
23-MAR-64.	1.	HV-21, & HV-22 ADDED.	R.W.C.	
	NO.	CHANGE	BY	APP.

SCALE: NONE
DATE: 13-NOV-63
DESIGNED: J. THOMAS
DRAWN: H.S.W.
CHECKED:
APP'D:

TOLERANCES UNLESS NOTED (NON-ACCUMULATIVE)
.XXX = ± .002"
.XX = ± .005"
FRACTIONS = ±1/32"
ANGLES = ± 1°

NO. REQ'D:
MAT'L:
FINISH UNLESS NOTED: √

TITLE: SHOCK TUBE GAS FLOW SCHEMATIC. 2

GUGGENHEIM LABORATORIES
DEPARTMENT OF AERONAUTICAL ENGINEERING
PRINCETON UNIVERSITY

DWG. NO. JP24-M999A REV I

FORM NO. 3765-2 D & W BLUEPRINT CO.

D-4-1

D-4-2

2 FIGURE D-2

Prior to firing a shot and with the shock tube open at the burst section, both sections of the shock tube are blown down with nitrogen gas to clean the tube. A diaphragm is put in place and the tube closed. With the test transducer installed, the test section is evacuated, purged with test gas and evacuated again. Test gas is admitted until the proper pressure level, indicated on an absolute pressure gage, is reached. Test pressure for a helium into nitrogen test at an anticipated 540 lb in^{-2} absolute burst pressure is 6.2 lb in^{-2} absolute for a shock speed of Mach 3.6. The test section is then sealed off by closing the small needle valves at the end of the tube. Pressurizing gas is admitted through a restricting (0.025 inch diameter) orifice until the diaphragm ruptures. The pressurizing gas supply valve is then closed and the tube is vented to atmosphere.

Transducer output data was gathered for computer analysis by placing the signal on a single beam oscilloscope and photographing the display on a polaroid camera. The camera lens was opened at approximately 530 lb in^{-2} absolute drive section pressure and the single sweep of the oscilloscope was triggered by the filtered output of a Kistler 601A transducer placed in the tube 12 inches upstream of the test transducer. Although various triggering systems using the output of a thin-film gage were employed, none were so dependable as the Kistler 601A - Model 566 Charge Amplifier combination with the ground shock filtered out of the signal.

3. Computer Analysis

Although one can readily approximate the various resonant frequencies, damping, overshoot and rise time directly from photographed shock tube data, little is gained with respect to transducer dynamic performance without a method of accurately extracting data from such photographs to be fed into a computer program whereby amplitude ratio and phase lag with frequency can be accurately determined. Various methods of approach to computer analysis of dynamic response of transducers to a step input have been reported. A detailed evaluation of any one would be tedious and simply a reproduction and will not be presented here. However, special attention should be directed towards reference (11) which presents the straight-line approximation for the evaluation of the frequency response of a pressure transducer from its dynamic response to a step input in detail.

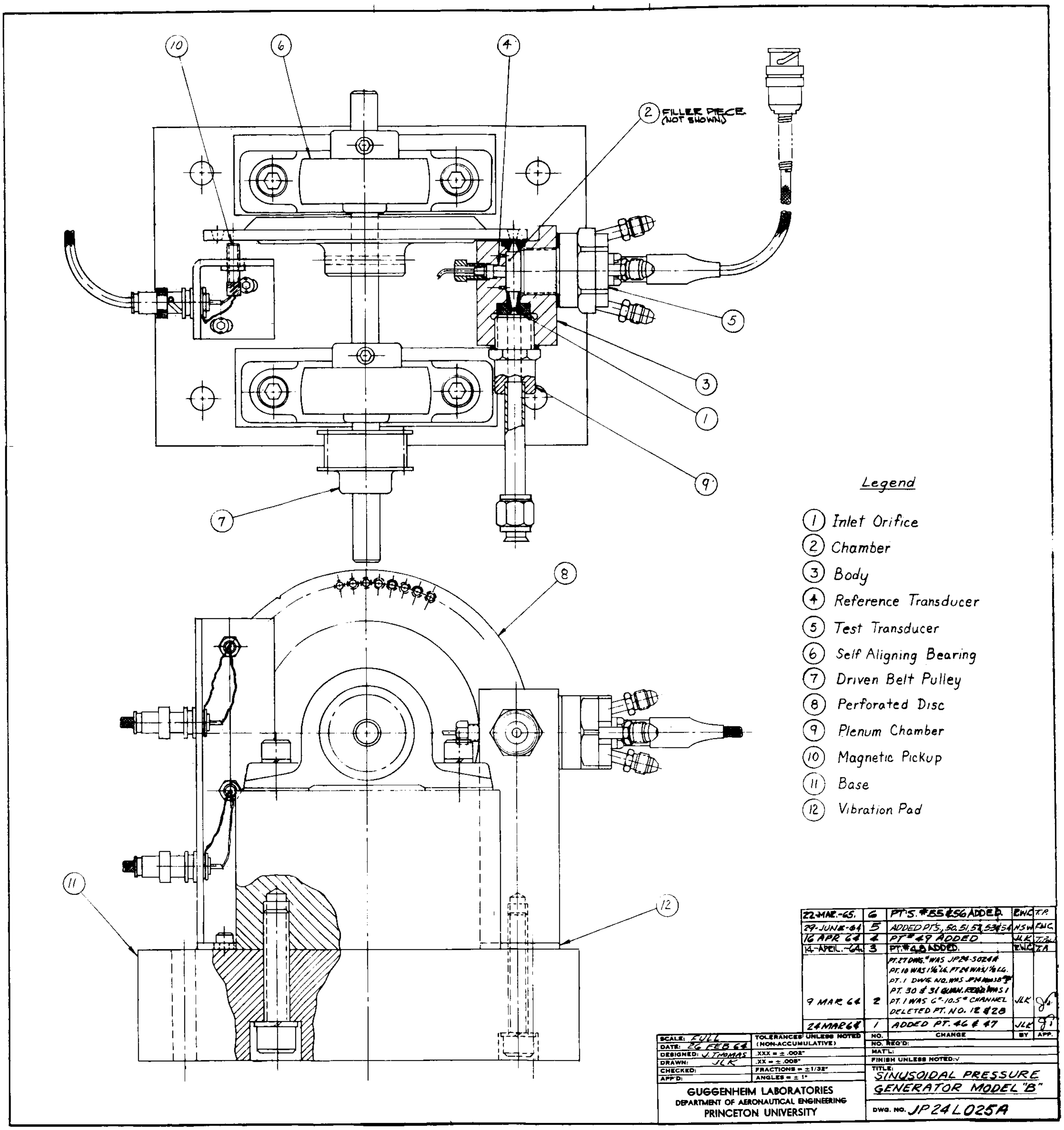
APPENDIX E: The Princeton Sinusoidal Pressure Generator

The Princeton Sinusoidal Pressure Generator is a gas throttling device, developed by H.B. Jones, with a designed function of determining the dynamic response of pressure transducers.

1. Design

The generator depicted in Figure 36 and in the drawing of Figure E-1, is the most recent version following several improvements in the machine developed in the work of reference (10). The cylindrical test chamber has a length of 0.250 inches and a diameter of 0.875 inches to accomodate the largest transducer evaluated during the research. Adaptors were used to fit all other transducers in the test chamber cavity designed about the Photocon model 352A-4925 transducer. The output of a Kistler 601A quartz transducer, having a natural frequency of 140,000 Hertz, was used to monitor test transducer output for all transducers and transducer systems evaluated.

The original 0.100 inch diameter test gas inlet orifice was replaced by a critical nozzle to prevent the propagation of chamber pressure disturbances upstream into the test gas feed system and which, in the interest of economy, had a throat sized to maintain helium gas consumption at a minimum while providing the desired average test chamber pressure. The perforated aluminum wheel, used to interrupt gas flow out of the test chamber, had served well for the low average chamber pressure of 55.5 lb in^{-2} absolute (10) in the original design. Increasing average chamber pressure showed a wheel deflection to exist which grew with increasing speed and a new wheel was fabricated of "stripper" plate steel with a high modulus of rigidity. Frequency, previously determined by the number of wheel perforations and a magnetic pickup of shaft



Drawing of Princeton Sinusoidal Pressure Generator

FIGURE E-1

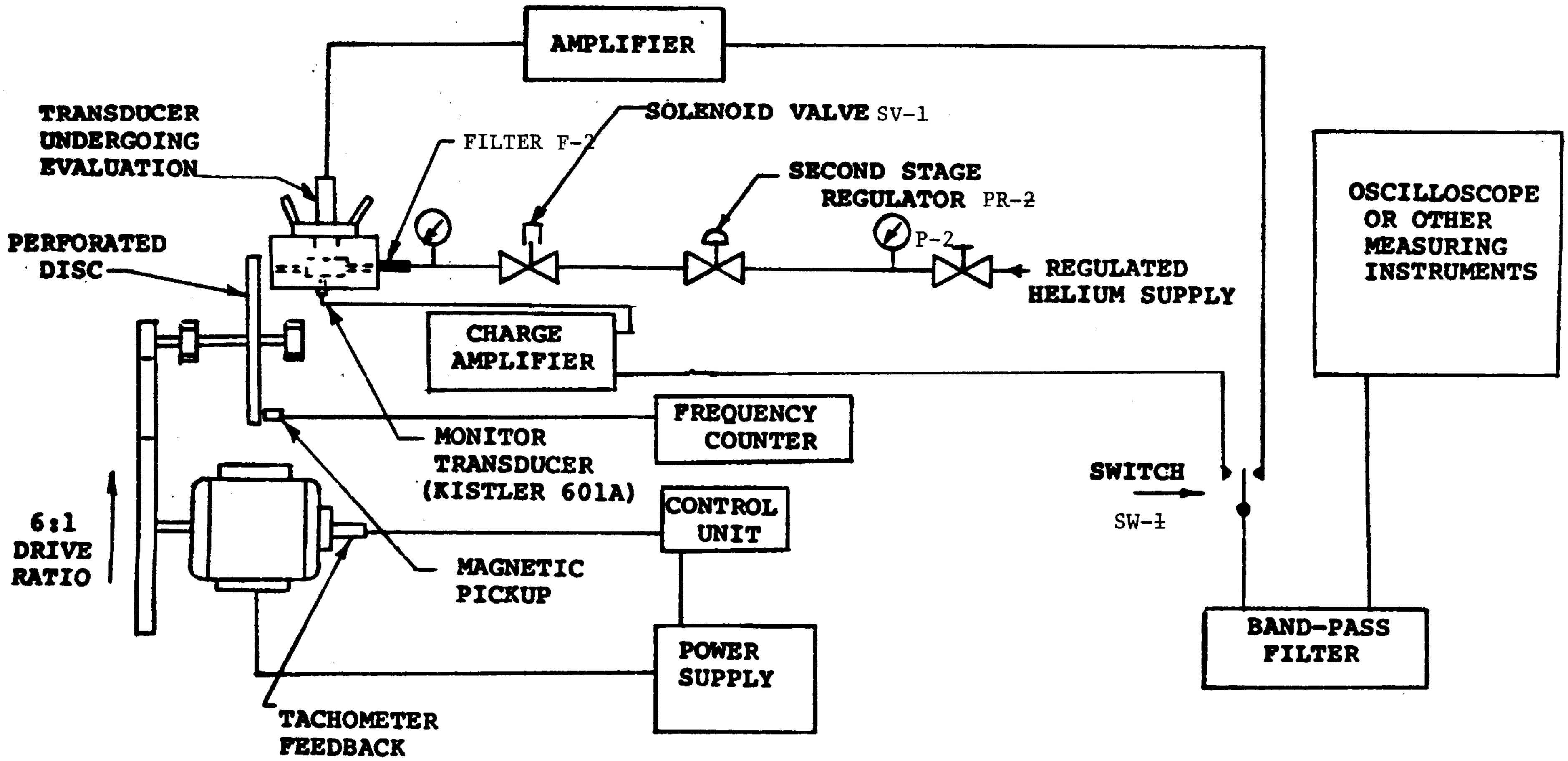
rpm, was determined by a small (1/32 inch) magnetic pickup aligned with the wheel perforations and whose output was placed directly on an electronic counter for monitoring. The vari-drive, used to drive the machine, was replaced by an adjustable-speed drive with a control head to set a predetermined frequency and which compared a highly regulated reference voltage with the output of a temperature-compensated d-c tachometer directly coupled to the drive motor. This change eliminated speed variations up to a frequency of approximately 6000 Hertz and allowed full frequency control to within $\pm$ 1.0 of 10,000 Hertz. All other changes in the original design were minor in nature and involved materials of construction, better access to adjustments and attachments of transducer appurtenances.

2. Operation

Following the schematic of Figure E-2, a predetermined frequency is set by adjusting a ten-turn potentiometer on the Speed Control Head and monitoring the output of the Magnetic Pickup on the Electronic Counter. When the counter indicates the frequency of interest, switch SW-1 is operated allowing helium to flow to the test chamber via solenoid valve SV-1 and filter F-2. Helium supply pressure to the test chamber is read on pressure gage P-2 and regulated by pressure regulator PR-2 to provide an inlet pressure 2.08 times or more greater than the peak pressure to be encountered in the test chamber. Test data is taken at the selected frequency and test gas is shut off while another frequency of interest is set by adjusting the potentiometer on the Speed Control Head. This process of operation is repeated until the test is completed.

3. Data Analysis

The primary purpose of dynamic testing in the SPG was to determine the Amplitude Ratio vs Frequency characteristic of transducers and



Schematic of Sinusoidal Pressure Generator System

FIGURE E-2

transducer systems undergoing evaluation. The instrumentation scheme presented in Figure 38 provided the necessary data to adequately determine amplitude ratio up to 10,000 Hertz ($\pm$ 10%). All data was reduced and plotted on an absolute basis.

Since the output of the monitoring Kistler 601A transducer as received from the charge amplifier was in the order of volts, amplification of the test transducer output was necessary to reduce the large difference in transducer outputs as seen by filters used to eliminate unwanted frequencies, including transducer natural frequency, from the data. The same filter received transducer signals from the amplifiers through a selector switch. This procedure eliminated corrections for the filter in data reduction. At any given frequency each signal was read individually on an rms voltmeter and recorded. Knowing the sensitivities of both monitor and test transducers from static pressure calibrations and applying a small correction for the amplifier in the test transducer circuit, rms values of transducer putputs are easily converted to amplitude ratio on an absolute basis and plotted as shown in Figure 25.

Other data for analysis which is readily available during evaluation in the SPG is pressure wave forms and phase relationship displayed on an oscilloscope and photographed. Frequencies, removed from the signals by narrow band filtering to accurately determine amplitude ratio, can be studied in the data displayed on a panoramic analyzer as shown in Figure 24.

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5 April 1967

FINAL SUMMARY TECHNICAL REPORT ON TRANSIENT PRESSURE MEASURING METHODS RESEARCH

Princeton University AMS Report No. 595t
31 March 1967

ERRATA

Page	Line	Change	To
10	9	spotted	reported
13	1	of instrument	of the instrument
13	17	resistance	resistive
15	17	0.015 mv	0.015 mv/psi
17	25	runs were made	runs made
17	26	RTU	RTV
24		Omit COMMENTS	
34	24	RYV	RTV
34	27	Remove "The"	
43	7	(9)	(10)
43	11	(5)	(7)
55	21	not	most
57	--	gage	gauge
57	12	charges	changes
61	9	limitations posed	limitations caused
82	--	Bulge arrow to similar location on upper cylindrical section	
A-1	24	595s	595r